Radioactive contamination of Danish Territory after core-melt accidents at the Barsebäck Power Plant

Gjørup, H.L.; Jensen, Niels Otto; Jensen, Per Hedemann; Kristensen, Leif; Nielsen, Ole John; Lundtang Petersen, Erik; Petersen, T.; Roed, Jørn; Thykier-Nielsen, Søren; Heikel Vinther, Frits

Total number of authors:
12

Publication date:
1982

Document Version
Publisher's PDF, also known as Version of record

Risø-R-462

RISØ

Risø-R-462

Radioactive Contamination of Danish Territory after Core-melt Accidents at the Barsebäck Power Plant

H. L. Gjørup, N. O. Jensen, P. Hedemann Jensen,
L. Kristensen, O. J. Nielsen, E. L. Petersen,
T. Petersen, J. Roed, S. Thykier-Nielsen,
F. Heikel Vinther, L. Warming, and A. Aarkrog

March 1982

Risø National Laboratory, DK-4000 Roskilde, Denmark

RISØ-R-462

RADIOACTIVE CONTAMINATION OF DANISH TERRITORY AFTER CORE-MELT ACCIDENTS AT THE BARSEBÄCK POWER PLANT

by H.L. Gjørup, N.O. Jensen, P. Hedemann Jensen,
L. Kristensen, O.J. Nielsen, E.L. Petersen,
T. Petersen, J. Roed, S. Thykier-Nielsen,
F. Heikel Vinther, L. Warming and A. Aarkrog

Abstract. An assessment is made of the radioactive contamination of Danish territory in the event of a core-melt accident at the Barsebäck nuclear power plant in Sweden.

Accidents including both core melt-down and containment failure are considered. Consequences are calculated for a BWR-3 release under common meteorological conditions and for a BWR-2 release under extreme meteorological conditions. Calculations are based on experiments and theoretical work relating to deposition velocities for different types of surface, shielding effect of structures, and weathering.

The effects are described of different dose-reducing measures, e.g., decontamination, relocation, destruction of contaminated foodstuffs. The collective effective dose equivalent from external gamma radiation from deposited activity integrated over a time period of 30 years, is calculated to be 3.6 Megamanrem

(continue on next page)

March 1982
Risø National Laboratory, DK-4000 Roskilde, Denmark

in the BWR-3 case without dose-reducing measures. For the BWR-2 case, the corresponding dose is approx. 41 Megamanrem. A combination of temporary relocation, hosing of roads etc. and digging of gardens is estimated to reduce these doses to approx. 2.5 Megamanrem and approx. 15 Megamanrem, respectively.

The collective committed effective dose equivalent from the consumption of contaminated foodstuffs is calculated to 23 Megamanrem in the BWR-3 case without dose-reducing measures. This dose could be reduced to 0.2 Megamanrem if contaminated crops are destroyed during the first year after the accident and if changes are made in agricultural production in the contaminated area. The corresponding doses in the BWR-2 case would be 197 Megamanrem and 1.4 Megamanrem, respectively.

INIS descriptors: MELTDOWN, METEOROLOGY, EXTERNAL RADIATION, GAMMA RADIATION, RADIATION DOSES, FALLOUT DEPOSITS, SURFACE CONTAMINATION, BUILDINGS, SHIELDING, WEATHER, FOOD CHAINS

UDC 519.283 : 614.73 : 614.876 : 621.039.58

ISBN 87-550-0831-3
ISSN 0106-2840

Risø repro 1982

LIST OF CONTENT

1. INTRODUCTION

At the request of the National Agency for Environmental Protection, Risø National Laboratory published calculations of the individual and population doses on Danish territory that might result in the event of core-melt accidents at the Barsebäck nuclear power plant in Sweden. This information was issued in 1977 in a report Risø-R-356 under the title "Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor".

In connection with this report Risø made different supplementary calculations for the Agency in the following years. These related, e.g., to the radioactive contamination of areas of land in Denmark that might result from such an accident.

However, because the Barsebäck plant lies close to Copenhagen, the Agency wished to have a more detailed treatment of the problem of land contamination, and thus a Working Group was set up in December 1978 to deal with this matter. The Group was to:

- Describe the fallout of radioactive material on Danish territory that might occur in the event of an accident at the Barsebäck plant. This description was to cover selected accident sequences and meteorological situations.
- Evaluate the possibility and the costs of different measures to limit the radiation level in areas affected by radioactive fallout.
- Evaluate to what degree utilization of the contaminated areas should be restricted. In continuation of this point the Group was to assess the consequences to society of such situations.

Apart from making use of the basic material relating to such work that was in the possession of or obtainable by the Agency and by the National Health Authority, the Group could ask for assistance from Risø, the civil defence authorities, the labour authorities, and any other relevant bodies.

The present report deals with the calculations and investigations carried out at Risø as a basis for the work of this Group.

Just as was the case in the previous report, the basic principle underlying the calculations was that unknown or uncertain factors should be evaluated very cautiously so that calculations would not underestimate the effects of an accident at Barsebäck. A number of conditions that were evaluated so cautiously in the previous report that they are considered to have contributed to a significant overestimation of the effects of an accident were more thoroughly investigated in the present case. In these areas it was thus possible to base the present calculations on more realistic assumptions. This applies in particular to such factors as deposition velocities, shielding effect of structures, as well as run-off and weathering.

Comparing the present report with the previous one, it should be noted that the meteorological conditions that have the most serious contamination consequences are <u>not</u> the same as those that give the greatest individual doses. For this reason, the meteorological assumptions on which this report is based are not the same as those treated in Risø Report 356.

There are no descriptions in the literature of work similar to what had to be carried out at Risø. This necessitated experiments to determine how the work could best be accomplished. Moreover, because activities had to be completed within a couple of years, calculations had to be carried out side by side with experimental work and with literature studies made in order to establish the assumptions on which to base the calculations. This left its mark on some of the methods used in the report. For example, it was not possible to take into account entirely correctly the variations from place to place of the deposition velocities because this would have required a more advanced dispersion model. However, the methods applied do not significantly increase the uncertainty.

Furthermore, because of the limited time available, it was only possible to carry out detailed calculations for two combinations of release and meteorological conditions; and, of these, major efforts were put into the most extreme combination.

In order to issue an English-language version of the present report within as short a space of time as possible, it was decided not to re-edit it with a view to readers abroad. The original Danish version was thus translated with little or no alteration, except for the deletion of some material that would be without interest for readers outside Denmark.

The authors are indebted to Mrs Jennifer Paris for carrying out the translation and to Mrs Karna Hansen for typing the report.

2. SUMMARY AND CONCLUSIONS

An evaluation was made of the long-term consequences of radioactive contamination of Danish territory after core-melt accidents at the nuclear power plant at Barsebäck, Sweden (20 km east of Copenhagen).

The effects of different dose-reducing measures such as decontamination, relocation and destruction of contaminated foodstuffs are described.

The calculations make use of the same release fractions for the radionuclides released by the reactor as used in the American Reactor Safety Study (NRC 75). Very recently, however, new evaluations of the possible magnitudes of radioactive releases have been published (Le 80, NRC 81).

In addition, in October 1981, the Swedish government decided that the Barsebäck plant should be furnished with a system that can reduce any overpressure in the reactor containment by means of ventilation through a filter system. In reality, this excludes any possibility of containment failure as a consequence of overpressure.

It was not possible to take this recent information into account in the present report.

2.1. The most probable consequences

The conditions that must prevail if an accident at Barsebäck is to affect Danish territory are: a melt-down of the reactor core and, at the same time, failure of the pressure-tight reactor containment and, finally, the wind must be blowing in the direction of Zealand.

If all three conditions are fulfilled, the result would probably be a combination of a BWR-3 release and weather conditions of Pasquill stability category D without precipitation and with a wind speed of 10 m/s.

Under such circumstances there would be no acute (non-stochastic) effects on the health of the population in the Zealand area, according to Risø Report 356.

Calculations in the present report show that the collective doses from such an accident would not exceed 0.6 Megamanrem from the passage of the cloud and 3.6 Megamanrem integrated over 30 years from the deposited activity. It would hardly be reasonable to relocate the population from the area other than from minor, local hot spots. As a result of fire-hosing of the roads within an area of approx. 20 km^2 and digging the gardens inside an area of some 150 km^2, the collective doses from deposited activity could be reduced by approx. 1 Megamanrem.

After such an accident, if the crops produced during the first year are destroyed and alterations are made in agricultural production inside an area of up to 3500 km^2, the collective dose as a result of the consumption of contaminated foodstuffs would not exceed 0.2 Megamanrem. (If, instead, only the crops are destroyed, then the collective dose would be maximum 4 Megamanrem. If no action is taken whatsoever, the corresponding dose would be maximum 23 Megamanrem).

Supplementary calculations show that it could prove necessary, in addition, to place restrictions on agricultural production on the island of Funen; otherwise agricultural products from this area could give a collective dose of up to 5 Megamanrem.

If the above-mentioned action is taken, an accident of the type concerned could result in a total collective dose that hardly exceeds 3.4 Megamanrem. Under the assumption that 1 Megamanrem results in approx. 100 deaths from cancer, the dose in question would imply approx. 340 deaths from cancer. In comparison, more than 200 000 of one million Danes (corresponding to the number affected by the release) "normally" die as a result of cancer.

The probability of a BWR-3 release occurring at Barsebäck is about 2×10^{-5} per reactor year if the accident frequency used in WASH-1400 can be applied to Barsebäck.

2.2. Extreme consequences

The most serious combination of accident circumstances, seen from the viewpoint of land contamination, would be a BWR-2 release under weather conditions of Pasquill stability category F with meandering, without precipitation and with a wind speed of 5 m/s.

Nevertheless, these circumstances would not lead to acute (non-stochastic) effects on the health of the population of Zealand.

The calculations published in the present report show that the collective dose would not exceed about 9 Megamanrem from the passage of the cloud and approximately 41 Megamanrem integrated over 30 years from external radiation from the deposited activity. Relocation of 100 000 people for the first month after the accident would reduce the collective dose from deposited activity by approximately 1 Megamanrem. Relocation of 600 000 people would reduce the dose by approximately 4 Megamanrem.

It appears unnecessary to limit occupational activities, even in areas where the population is otherwise relocated. This is because the hours in which work usually takes place comprise only a fraction of the hours of a week and because work normally takes place in large, well shielded buildings. It cannot be excluded that it might be necessary to place restrictions on a few places of work, but the most important functions of society could be maintained.

A further reduction of the collective dose by approximately 21 Megamanrem could be achieved by fire-hosing the roads inside an area of approx. 130 km^2 and by digging the gardens of houses inside an area of 1400 km^2. This would reduce the collective dose integrated over 30 years from external radiation from deposited activity to approximately 15 Megamanrem.

If it is deemed appropriate to reduce the collective dose still further, the report describes a number of other measures that could be applied.

If the crops growing during the first year after such an accident are destroyed and alterations are made in agricultural production inside an area of up to 3500 km^2, the collective dose as a result of the consumption of contaminated foodstuffs can be kept below 1.4 Megamanrem. (If only the crops are destroyed, the collective dose would be maximum 29 Megamanrem. If no action is taken, the corresponding dose would be maximum 197 Megamanrem). Supplementary calculations show that, in addition, it could be necessary to place restrictions on agricultural production on the island of Funen; otherwise agricultural products from this area could give a collective dose of up to 8 Megamanrem.

If these measures are implemented, this extreme accident case could only imply a collective dose of up to about 25 Megamanrem, which would result in up to 2500 deaths from cancer. As mentioned previously, there would "normally" occur more than 200 000 deaths from cancer in a population group of this size.

The probability that a release from Barsebäck would affect the metropolitan area of Copenhagen under meteorological conditions classed as Pasquill F is about 0.5% (cf. Risø Report 356). If the accident frequency used in WASH-1400 is applicable, the probability of a BWR-2 release occurring at Barsebäck is about 6×10^{-6}. This means that the probability of the consequences described above is about 3×10^{-8} (which corresponds on average to once per 30 000 000 reactor operation years).

2.3. Uncertainties

The whole character of the present work implies that the calculations presented in this report are associated with considerable uncertainty. There are, however, some factors that should be taken into account.

For the individual, the risk that he/she will suffer from cancer as a result of the accident just described depends on the radiation dose he/she receives - but even the largest radiation doses that might occur without decontamination procedures would only imply a slight increase of the already existing probability of suffering from cancer.

Thus the collective doses and not the individual doses should be the focus of attention. This means that the uncertainty associated with the behaviour of the individual, or with the exact geographical distribution of the contamination, etc., becomes less significant because the uncertainty of the calculated individual dose levels is smoothed out when these are summed over a larger population group.

Another factor that should be noted is that the calculations tend to overestimate the effects, because conditions of which there is only little knowledge are estimated very cautiously. In connection with the effects of land contamination for so long a period of time as 30 years, it is obvious that during this time changes would invariably be made that would remove contamination - e.g., renewal of road surfaces, demolition of buildings, re-roofing, etc. In contrast it is extremely difficult to envisage any circumstances that would increase the dose rate.

Despite the difficulty inherent in assessing the uncertainty of these calculations, it is most probable that the doses that might occur from such an accident would be significantly smaller than those calculated in the present report.

References

LE 80 Levenson, M. and Rahn, P., 1980 "Realistic Estimates of the Consequences of Nuclear Accidents", Electric Power Research Institute, Palo Alto, California.

NRC 75 NRC,1975, "Reactor Safety Study, An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants", WASH-1400 (NUREG-75/014).

NRC 81 NRC, 1981, "Regulatory Impact of Nuclear Reactor Accident Source Term Assumptions", NUREG-0771, Appendix (A).

3. TYPES OF ACCIDENT AND MAGNITUDES OF RELEASE

3.1. Assumptions

For the evaluation of the consequences of land contamination in the event of a serious accident at Barsebäck, the Working Group set up two requirements pertaining to the determination of the amount of radioactive material that might be released from the reactors. The first was that the release should be calculated on the basis of (internationally) established models. The second was that the type of accident should be selected so that the calculated consequences of contamination would be the greatest possible.

The first requirement implied that the starting-point for the calculations would be the release categories used in WASH-1400 (NRC 75). To date, two comprehensive investigations of the release of radioactive material from nuclear power stations in given accident scenarios have been published. One is WASH-1400 and the other is the risk study carried out in the Federal Republic of Germany. In the present version of the latter, however, the release calculations are based on the models and methods used in the WASH-1400 study, but applied to a German reactor. In addition, this study does not concern a boiling-water reactor but a pressurized-water reactor - the Barsebäck reactors are of the former type.

As caesium is a radioactive material that might be released in relatively large amounts during an accident owing to its low boiling point, and because it has a long half-life (approx. 30 years), Cs contamination might be of long duration. On this background, it appears that the second requirement implies a choice amongst accidents giving the largest releases of Cs.

3.2. Release category

The WASH-1400 release categories that give the greatest release of radioactive materials are termed BWR-1 and BWR-2. The release of Cs in the two cases is 40% and 50%, respectively, of the total content of Cs in the reactor core at the start of the accident. Release category BWR-2 was thus chosen as the starting-point for calculating the contamination subsequent to an accident.

The composition of the release, in categories 1-4, is given in table 3.1. For the isotopes of greatest importance from the radiological viewpoint, the table gives the release to the surroundings in % of the total content in the reactor core of the nuclides concerned at the start of the accident.

Table 3.1. Release in % of total content

Isotopes	BWR-1	BWR-2	BWR-3	BWR-4
Xenon, krypton	100	100	100	60
Iodine, bromine	40	90	10	0.08
Caesium, rubidium	40	50	10	0.5
Tellurium, tin	70	30	30	0.4
Barium, strontium	5	10	1	0.06
Ruthenium, molybdenum	50	3	2	0.06
Lanthanum, cerium, neptunium	0.5	0.4	0.3	0.01

The total content of radioactive isotopes was calculated applying the same assumptions as used in WASH-1400, but taking into account the fact that the Barsebäck reactors are smaller than the Peach Bottom reactor used in the WASH-1400 study (He 77). The contents appear from table 3.2.

Table 3.2. Fission product inventory of the Barsebäck reactor. Activity in MCi. T_K is the time elapsed since the start of the accident.

Isotope	T_K=0	T_K=2h	T_K=30h
Co 58	0.78	0.78	0.77
Co 60	0.29	0.29	0.29
Kr 85	0.45	0.45	0.45
Kr 85m	16.60	12.30	0.15
Kr 87	29.90	10.00	0.00
Kr 88	42.20	25.70	0.025
Rb 86	0.014	0.014	0.013
Sr 89	43.90	43.80	43.80
Sr 90	3.53	3.53	3.53
Sr 91	75.30	65.30	8.78
Y 90	3.60	3.60	3.58
Y 91	56.50	56.50	55.70
Zr 95	75.10	75.10	74.10
Zr 97	81.40	75.10	24.00
Nb 95	75.50	75.50	75.50
Mo 99	81.60	79.80	59.50
Tc 99m	77.40	77.20	61.90
Ru 103	66.90	66.90	66.90
Ru 105	24.50	18.60	0.24
Ru 106	10.60	10.60	10.60
Rh 105	39.40	37.90	22.10
Te 127	2.53	2.53	2.33
Te 127m	0.38	0.38	0.38
Te 129	14.70	13.20	1.63
Te 129m	2.40	2.39	2.34
Te 131m	6.56	6.27	3.28
Te 132	60.30	59.20	46.00
Sb 127	1.85	1.82	1.47
Sb 129	15.50	11.30	0.12
I 131	46.60	46.40	42.40
I 132	62.90	63.50	51.10
I 133	90.10	84.00	33.00
I 134	111.11	47.70	0.00
I 135	85.50	69.60	3.83
Xe 133	89.30	89.30	84.10
Xe 135	25.80	32.90	16.30
Cs 134	3.00	3.00	3.00
Cs 136	0.82	0.82	0.77
Cs 137	4.52	4.52	4.52
Ba 140	79.30	78.90	74.10
La 140	80.50	80.50	78.80
Ce 141	74.00	74.00	72.10
Ce 143	69.60	66.70	37.00
Ce 144	57.10	57.10	57.00
Pr 143	69.40	69.40	68.30
Nd 147	30.30	30.20	28.00
Np 239	901.20	883.80	624.80
Pu 238	0.03	0.03	0.03
Pu 239	0.01	0.01	0.01
Pu 240	0.01	0.01	0.01
Pu 241	1.80	1.80	1.80
Am 241	0.001	0.001	0.001
Cm 242	0.27	0.27	0.27
Cm 244	0.012	0.012	0.012

3.3. Accident sequences

The release discussed in the foregoing section is not the result of a certain chain of accident events; it is representative of a number of chains of event that are identified in WASH-1400.

A large part of the probability for the occurrence of a BWR-2 release originates from an accident starting with a non-defined transient that results in shut-down of the reactor, i.e. the fission process is brought to a standstill. Because of the content of radioactive materials in the fuel, heat would still be generated. Hereafter, all the systems that should carry heat away from the reactor tank and condensation basin at the bottom of the reactor containment are assumed to fail. Thus, the condensation basin is heated so much that steam pressure leads to a rupture of the reactor containment. It is furthermore assumed that the containment fails in such a way that it gives direct pathway from the containment to the surroundings of the plant. Some time later the water in the reactor tank boils away and the core starts to melt. During the melt-down a very large part of the more volatile fission products (including Cs) would be released from the fuel because of the high temperature (1800-2400^{o}C) and because of the large surface area of the molten fuel. The flow of steam and hydrogen, in which the hydrogen is created through a reaction between water and metal in the reactor core, can now transport the radioactive materials from the reactor tank via the containment out to the surrounding area.

The other accident sequences that lead to a BWR-2 release start with a loss-of-coolant accident with subsequent failure of all emergency cooling systems. The reactor tank is thus emptied of water after a longer or shorter time period. The reactor core is then entirely without cooling and melts. Only when a large portion of the core has melted will the molten material fall to the bottom of the reactor tank. After roughly half an hour the molten material melts through the reactor tank and falls to the floor below the tank.

Hereafter it is assumed that there is either a steam explosion when the molten metal comes into contact with the water, or that there is a rather slower build-up of pressure because of the generation of steam and gas (hydrogen and carbon dioxide) on contact between the molten metal, water and concrete. In both cases the reactor containment is presumed to fail, leading to a direct pathway from the containment to the environment. Again it is the flow of gases and steam that transports the radioactive materials to the outside area.

Thus the common factor in accident sequences leading to a BWR-2 release is that the accident involves a failure of the reactor containment, giving a direct pathway to the environment. Should the failure take place so that the building surrounding the containment is little damaged, or damaged in such a way that the transport of radioactive materials takes place via the reactor building, then this acts as a filter and the release is substantially reduced. This filter effect is the result of a tendency of the radioactive materials to settle on walls and objects inside the reactor building. (If the filter effect is manifested, then the release is that termed in WASH-1400 a BWR-3, instead of a BWR-2).

3.4. Comparison between WASH-1400 and Barsebäck

Calculations relating to the WASH-1400 BWR-2 release used in this study were based on the construction of the Peach Bottom reactor in the USA. Thus it is of interest to investigate if the differences in the construction of the Barsebäck reactors and that at Peach Bottom have any significant influence on the results.

Taking constructional differences into account, the main assumptions for a release of BWR-2 character will be the same. Hence the accident must involve a core melt-down, and there must be a failure of the reactor containment leading to a direct pathway to the environment.

For the accident sequences where the reactor containment fails before the core starts to melt, there is no reason to assume that the release at the start of an accident at Barsebäck or at Peach Bottom would differ significantly. Taking appropriate account of the size of the reactors, the amounts of gas and steam that would be generated during the melt-down would not differ; furthermore it is assumed that direct access to the surroundings would be established. The decontamination processes that might affect the release would depend on the volumes and cross sectional areas of the reactor tanks and containments. Relatively viewed, these values are just about equal, so there is no reason to presume that the retention of radioactive materials would differ very much in the two set-ups.

On the other hand, the later stages of the accident and the accident sequences where the containment fails after the molten core falls to the ground inside the containment could well develop differently in the two types of reactor. This is because the concrete of the Barsebäck plant, in contrast to that at Peach Bottom, does not contain a limestone aggregate. In addition, the flooring beneath the reactor tank at Barsebäck is approximately 1 m thick and below this lies the condensation basin. The small content of limestone in the Barsebäck concrete implies a lesser generation of carbon dioxide on interaction with the melt. This in turn means that there would be less gas to transport radioactive materials, and thus a smaller release. However, if a large part of the radioactive material was released already during the melt-down and transported out to the surroundings, then a BWR-2 release might result after all.

For sequences where the containment fails later in the accident, the production of less carbon dioxide implies a delay of the failure, in addition to less transport of radioactive material. This delay would presumably bring about a further reduction in the release of the specially volatile fission products (e.g., Cs). These would be released from the molten fuel at an early stage of the accident, and thus be released into the containment before this failed. Therefore there is a possibility that the radioactive material is deposited in the containment before the start of the release. In addition, the reduced production of gas reduces the flow rates.

If the concrete flooring is melted through, the molten core falls into the condensation basin. Contact between the melt and the water would lead to intense generation of steam and - with slight probability - a steam explosion. In both cases there is a chance that the containment would fail - if it had not done so already. However, there is also a possibility that the melt cools down and that steps could be taken to cool it further, without any failure taking place. If steps can be taken to continue to cool the melt, then no further release takes place.

Therefore the differences between Barsebäck and Peach Bottom are no greater than that it is reasonable to assume that a BWR-2 release could take place at Barsebäck, just as it could at Peach Bottom.

3.5. Probability of the BWR-2 release category

According to WASH-1400 the probability of a BWR-2 release is $6 \cdot 10^{-6}$ per reactor year.

As mentioned earlier, it was decided in the present investigation to study the consequences of accidents involving a large release and especially those involving a large release of Cs. In the case of a boiling-water reactor the two categories giving the greatest release are BWR-1 and BWR-2. The difference in Cs release between BWR-1 and BWR-2 is not, however, greater than that the probability of a large Cs release should be calculated as the sum of the probabilities of the BWR-1 and BWR-2 releases. This is, however, of little importance because the probability of a BWR-1 release is 10^{-6} per reactor year according to WASH-1400. The resulting probability of a large Cs release then only increases from $6 \cdot 10^{-6}$ to $7 \cdot 10^{-6}$ per reactor year.

Moreover, recent investigations seem to prove that a BWR-1 release would not be able to take place at all. A BWR-1 release implies, namely, the occurrence of a steam explosion in the reactor tank that leads to failure of the tank and containment when the molten core falls to the bottom of the tank.

Sandia Laboratories recently carried out a number of studies concerning, e.g., steam explosions in a reactor tank (Be 80). These primarily concerned pressurized-water reactors. The result was reached that the probability of a steam explosion following a core melt-down, leading to containment failure, is 100 times less than the value reached in WASH-1400. The probability for containment failure resulting from a steam explosion in the reactor tank after a core melt-down is thus estimated to be approximately 10^{-4}. Moreover, the Sandia investigations seem to indicate that reasons will be found for lowering this value still further so that, in practice, the possibility of a steam explosion with subsequent containment failure can be entirely ruled out.

A similar conclusion was reached in Sweden. Here an expert committee, set up by the government in 1980, concluded on the basis of present knowledge and on hearings of experts from the USA and the Federal Republic of Germany, that the design of safety systems for a reactor, and plans for emergencies, did not need to take into account accidents involving steam explosions of an intensity that could lead to failure of the reactor tank or containment (In 80).

Moreover, for Barsebäck, studies are presently being made of special filters connected to the containment. Such filters would consist of a very large space filled with stones followed by a large sand filter. This arrangement will be connected with the reactor containment by a tube having a large diameter. This would be closed by a safety valve or rupture disk during normal reactor operation. If pressure in the containment rises to close that which leads to containment failure, passage to the filter system is opened. The volume of this system and the heat capacity of the contents are large enough to prevent the steam and gases produced by a core melt-down from raising the pressure in the containment and filter chamber to close to the ultimate until after a suitable length of time has elapsed. In this manner the majority of the radioactive material would be deposited in the containment and filter. Should the pressure again reach values where there is risk of failure, controlled ventilation of the filter chamber can be effected. At the point in time when this might take place, the amount of radioactive gases and aerosols that could be released would have been reduced by several orders of magnitude. Exceptions would, of course, be the noble gases that are not trapped in filters and the like. However, the release of the radioactive noble gases is less serious than that of other materials because these gases do not take part in the biological chains.

A filter arrangement such as that described can be expected to function with great reliability. As such filters are expected to be installed at Barsebäck in 1986, the probabilities of a core melt-down leading to a BWR-2 or BWR-3 release are reduced, and the largest release that can then be expected with some probability to result from a core melt accident is in the BWR-4 category (see table 3.1).

3.6. References

Be 80 Berman, M. et al., 1980, "U.S. Steam Explosion Research: Risk Perspective and Experimental Results". Lecture held at Kernforschungscentrum Karlsruhe during Project Nukleare Sicherheit Jahreskolloqium 1980.

He 77 Hedemann Jensen, P. et al., 1977, "Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor", Risø Report 356.

In 80 Industridepartementet, 1980, Ångexplosioner i Lättvattenreaktorer, Betänkande av Ångexplosionskommittén, Ds I 1980: 28. (Steam explosions in light-water reactors. Report by the Steam Explosion Committee).

NRC 75 NRC, 1975, "Reactor Safety Study, An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants" WASH-1400 (NUREG-75/014).

4. DEPOSITION VELOCITIES (wet and dry)

4.1. Introduction

Matter, particulate or gaseous, is transferred from the atmosphere to surfaces by a number of different processes. These processes are collectively called deposition. Deposition depends on three types of parameter: parameters describing the matter to be deposited (particle size, distribution, etc.), meteorological parameters (temperature, humidity, wind velocity, etc.) and surface parameters (vegetation type, density, physiology, etc.)

The concept of deposition velocity, v_g, was introduced by Chamberlain in 1953 (Ch 53). He defined v_g as

$$v_g(z) = F/X(x,y,z) \tag{4.1}$$

where F is the flux to the surface, i.e. material deposited (in g or curie) per unit area and time, and X(x,y,z) is the volumetric concentration in the air at a reference point (x,y,z) above the surface. v_g can also be defined as

$$v_g(z) = F_T/X_T(x,y,z) \tag{4.2}$$

where F_T is the total amount of material deposited per unit area and $X_T(x,y,z)$ is the corresponding time integral of the concentration in the air. It should be noted that v_g is a function of reference height to the surface. The normal reference height is 1 m above ground, and v_g is normally given in the unit cm/s.

When discussing deposition velocities it is appropriate to divide the deposition processes into different groups according to types of material (gases, particles), meteorological conditions (dry or wet deposition), and types of surface (rough and smooth surfaces). All deposition processes are described in detail in a recent report (Ni 81).

As main emphasis was placed on the dry situation in the dose calculations in the present report, dry deposition is treated in greatest detail.

4.2. Dry deposition on rough surfaces

The term rough or pervious surfaces denotes surfaces covered by vegetation, such as fields.

4.2.1. Gases

For dry deposition of the gases associated with a reactor accident, it is only necessary to consider elementary iodine and gaseous compounds containing iodine, e.g., methyl iodine (CH_3I). There are many experimental determinations of deposition velocities for iodine on rough surfaces (He 80, Se 80, Ni 81).

It is important to realise that gases cannot be deposited more rapidly than they can be transported to the surface by the turbulent flow. This means that if, very pessimistically, one assumes a perfectly absorbing surface, v_g will always be less than u_*^2/u where u_* is the friction velocity and u is the wind speed. For typical values $u_* = 0.3$ m/s and u = 5 m/s, a maximum v_g value is obtained of 1.8 cm/s. In practice, however, v_g will always be somewhat smaller.

Using the many experimental determinations of dry-deposition velocities for iodine as a basis, it can be concluded that a typical v_g value for iodine can be put at 0.7 cm/s, and that it would be very improbable that v_g for iodine would exceed 1 cm/s. For methyl iodine, v_g is approximately 100 times less than for iodine.

4.2.2. Particles

Radioactive material is absorbed more or less effectively on particles in the atmosphere. Dry deposition of particles takes place by mechanisms which are radically different from those by which gases are transferred. Particles are deposited either by sedimentation or by collision. The relative frequency of these processes depends primarily on particle diameter.

As in the case of gases, matter cannot be deposited more rapidly than it can be transported to the surface. The maximum value of v_g is the sum of u_*^2/u and the sedimentation velocity v_s

$$v_s = \frac{s^2 \cdot g \cdot \rho_p}{18 \cdot \nu \cdot \rho} \qquad (4.3)$$

where s is the particle diameter, g is the acceleration of gravity, ρ_p and ρ are the density of, respectively, the particle and the air, and ν is the kinematic viscosity of air (0.15 cm^2 s^{-1} at 20°C).

As mentioned above, v_g depends primarily on the particle diameter. To find the deposition velocities for an aerosol, knowledge is thus needed of the distribution of particle sizes of the aerosol. Normally this knowledge is limited. For aerosols associated with reactor accidents, v_g can be put at 1 cm/s (Se 80). It is very convenient to be able to use the same deposition velocity for gases and for particles. As a common deposition velocity for rough surfaces, use is made in the present report of the value 2 cm/s. This choice is cautious with respect to shorter distances, i.e., the most heavily contaminated areas, whereas it might lead to an underestimation of contamination at greater distances.

4.3. Dry deposition on smooth surfaces

Smooth or impervious surfaces are envisaged as those of roads, the walls and roofs of structures, ground surfaces without vegetation, etc. As the greatest population concentrations are found in towns, it is very important to have a good determination of deposition on smooth surfaces. In WASH-1400 it was pointed out that there were only few experimental determinations of deposition velocities for smooth surfaces, especially for paved areas (pavements, roads, roofs and walls of structures, etc.). Since then, only few further data have appeared (Ho 76, Jo 79). These studies gave deposition velocities in the interval 0.02 to 0.03 cm/s, i.e., approximately a factor 100 lower than the v_g used for rough surfaces in the present report. This is in good agreement with a measurement of the accumulated dry deposition of fallout caesium on a covered, brick wall, which was carried out by Roed (Ro 81). This author finds that dry deposition on smooth surfaces is roughly a factor 80 less than on fields. As the deposition velocity of fallout strontium on fields is around 0.2 cm/s (Aa 79) and not 2 cm/s as used in the present report, it is very cautious to put the deposition velocity on smooth surfaces at 0.2 cm/s as is the case in the present report.

4.4. Wet deposition

The terminology dealing with wet deposition used in the literature is not entirely unambiguous. The term wash-out can just as well be used instead of wet deposition. The possibility of wash-out is determined by localization of the clouds, and by the intensity of the precipitation - both of which can be stated explicitly. Details such as the shapes of snow crystals and the distribution of raindrop sizes are also of importance, but normally these cannot be specified.

The properties of the material that is washed out are also of importance. Firstly, the material can be either particulate (e.g. caesium) or gaseous (e.g. iodine). Hence properties like particle size distribution and reactivity towards water are important. The latter is clearly demonstrated by the two orders of magnitude difference between the wash-out of iodine and that of bromine - this can be attributed to the fact that bromine is a hundred times more reactive towards water than iodine.

Regardless of the type of material, wash-out is generally described as an exponential process

$$X(t) = X(0)\ \exp(-\Lambda \cdot t) \qquad (4.4)$$

where X(t) is the concentration of the material remaining after a time t, X(0) the concentration at time zero, and Λ is the wash-out coefficient that represents the amount of material removed from the cloud per unit time.

Λ is often expressed (Mc 79, Gy 80) as

$$\Lambda = c \cdot p^a \qquad (4.5)$$

where c is a constant in s^{-1}, p is the intensity of the precipitation in mm/hr and a is an exponent in the interval 0.75 to 1.0.

Experimental determinations of Λ are few and very uncertain. The results indicate that Λ for gaseous iodine is of the magnitude $10^{-6}\ s^{-1}$ (En 66). Λ for particles can be put at $10^{-5}\ s^{-1} \cdot p$. There are no reasons for imagining that snow wash-out is more effective than rain wash-out (En 66).

4.5. References

Aa 79 Aarkrog, A., 1979, "Environmental studies on radioecological sensitivity and variability", Risø-R-437.

Ch 53 Chamberlain, A.C., 1953, "Aspects of travel and deposition of aerosols and vapour clouds", A.E.R.E. HP/R 1261.

En 66 Engelmann, R.J. et al., 1966, "Washout coefficients for selected gases and particulates", BNWL-Sa-657.

Gy 80 Gyllander, C. and Widemo, U., 1980, "Wet deposition-aerosols", K2-80/271, Studsvik.

He 80 Heinemann, K. and Vogt, K.J., 1980, "Measurements of the deposition of iodine onto vegetation and of the biological half-life of iodine on vegetation", Health Physics 39, 463-502.

Ho 76 Horbert, M. et al., 1976, "Untersuchungen zur Ablagerung von Aerosolen auf Vegetation und anderen Grenzflächen", Jül-1288.

Jo 79 Jonas, R., 1979, "Statusbericht über die Feldversuche zur Bestimmung der Ablagerungsgeschwindigkeit von Aerosolen", ZST-Bericht No. 295.

Mc 79 McMahon, T.A., 1979, "Empirical atmospheric deposition parameters - a survey", Atmospheric Environment 13, 571-585.

Ni 81 Nielsen, O.J., 1981, "A literature review on radioactivity transfer to plants and soil". Risø-R-450.

Ro 81 Roed, J., 1981, "Overfladedeponering af luftbåret materiale frigjort ved kernenedsmeltningsuheld i kraftreaktorer", (Surface deposition of airborne materials released in core-melt accidents at nuclear reactors). Risø-M-2274.

Se 80 Sehmel, G.A., 1980, "Particle and Gas Dry Deposition: A Review", Atmospheric Environment 14, 983-1011.

5. METEOROLOGY

5.1. Introduction

The materials that are released to the atmosphere following an accident in a nuclear power plant are to a large extent gases, droplets, and small particles, and these may be carried far away by the wind in the same way as the exhaust from a smoke stack. The simplest picture of the atmospheric transport mechanism is that of a horizontal plume, made up of the released airborne material, and lined up with the direction of the wind. The vertical and horizontal dimensions of this plume will increase with increasing distance from the source because of the turbulent mixing.

In the plume the concentration of the effluent will be determined mainly by the rate of release, the distance from the source, the wind speed, the turbulence, and the removal by dry and wet deposition.

The calculation of concentrations of radioactive material following a nuclear accident at Barsebäck will be based on such a simple plume picture, namely the so-called Gaussian plume model, and knowledge of the climatology in the area that can be affected is consequently essential.

In the following the Gaussian plume model will be discussed, together with the influence of the state of the atmosphere on its parameters.

5.2. The Gaussian plume model

The smoke issuing from a stack is only in exceptional cases shaped as a smooth, horizontal cone with a straight axis. The exact deviation of the shape from this "ideal" is difficult to determine, but fortunately it seems that in many cases (see, e.g., Gi 68) the shape of the plume becomes quite regular if averaged over a few minutes. This smooth average plume is really what the Gaussian plume model is able to describe.

In its simplest form, the model is a statement about the concentration X as function of the coordinates x, y, and z in a coordinate system with the origin in the source, which is considered to be a point source, the x-axis in the mean wind direction, and the z-axis vertical:

$$X(x,y,z) = \frac{Q}{2\pi u\ \sigma_y\ \sigma_z} \exp\left(- \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right) . \qquad (5.1)$$

Here Q is the source strength in, for example, Ci s^{-1}, u the wind speed, and σ_y and σ_z the distances in the vertical and lateral directions from the axis at which for a particular x the concentration has fallen to $1/\sqrt{e} \sim 0.6$ of that at the axis. The two so-called dispersion parameters σ_y and σ_z are for given atmospheric conditions functions of x only. The way in which σ_y and σ_z change with changing atmospheric parameters reflects, together with the wind speed, the capability of the atmosphere to dilute the released material.

The only atmospheric quantities entering directly into (5.1) are wind speed and wind direction, which define the coordinate system.

Time does not appear explicitly in the Gaussian plume picture, and one can imagine that (5.1) describes a tube, extending from the source to infinity, through which material is pushed at speed u. As the amount crossing a vertical cross section per unit time is proportional to u, and as the amount that has to be transported away per unit time is constant, the concentration must be inversely proportional to u.

As a rule the Gaussian plume model is not used in the form (5.1) because the presence of the ground, or equivalently the effect of the finite height H of the release point, must be taken into account. It is generally assumed that the dispersed material is reflected at the ground so that the effect of the release height is accounted for by introducing an imaginary additional source in the mirror image with respect to the ground. Instead of (5.1) the concentration becomes

$$X(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \times \left\{\exp\left(-\frac{z^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+2H)^2}{2\sigma_z^2}\right)\right\} \tag{5.2}$$

The technical details of the application of the Gaussian plume model in the Risø Model are given in Th 80.

In the following two subsections the applicability of the model and the influence of the state of the atmosphere on its parameters are discussed.

5.2.1. General applicability of the model

So far only one condition for the validity of the Gaussian model has been mentioned, namely that the rough outlines of the instantaneous plume must be smoothed over a period of time to make it conform to the shape of a Gaussian plume. However, by this stage a number of assumptions have been made for the application of the model in the case of the dispersion of airborne material from a source of pollution.

Firstly, the atmospheric turbulence must be homogeneous and statistically stationary. This implies - in non-technical terms - that there is statistically no beginning and no end, in space or in time, of the turbulent wind field. Of course, the atmosphere is not that ideal and consequently this assumption can at best be only approximately true. The diurnal variation of the atmospheric parameters, for example, will totally invalidate stationarity over periods of more than a few hours. Further, the sudden changes at sunrise and sunset may cause the atmosphere to respond in such a way that the stationarity assumption will not be even approximately true, however brief the period of time. Terrain features such as hills, valleys, trees, buildings, and even changes in the horizontal directions of crops, on the other hand, can bring into doubt the assumption of homogeneity in the horizontal directions. Most importantly, the very presence of the ground seems to violate even the idea of homogeneity in the vertical direction. Because the wind speed is zero at the ground, there must be a wind shear that will only gradually disappear with distance from the ground. Therefore the Gaussian plume model should not be expected to be any good if the source is too close to the ground. However, because the parameters used in the model are fitted to experimental data from releases close to the ground, the model usually performs reasonably well in such situations.

Formulas (5.1) and (5.2) indicate that the pollutants are transported in the wind direction by the mean wind and diffuse vertically and laterally because of turbulent motion. The effect of turbulence on longitudinal transport is entirely ignored. A sufficient condition for this to be a good approximation is that the root mean square wind speed σ_u is small compared to u. Usually this is not the case when u is small (say less than 0.5 ms^{-1}), and under such circumstances there is so little transport away from the source that a plume is not formed at all. If u has a finite magnitude at the same time as σ_u/u is not small compared to unity, the longitudinal turbulent transport may be neglected and the plume picture restored, if the distance x from the source is large compared to the horizontal spatial scale of the turbulence.

It has already been mentioned that time does not enter explicitly into the Gaussian plume formula. It may enter indirectly though, through σ_y and σ_z. Time can also be considered as entering through the source strength Q and the wind speed u. This is conceptionally a contradiction to the assumption about stationarity, at least as far as u is concerned, but a possible way to deal with time-varying wet deposition on the ground, resulting from a time-varying precipitation rate, is to ascribe the corresponding dilution of the plume to a time variation in Q. Real time variation in Q, corresponding to the fact that a physical source must at least have a time of start and a time of stop can be thought of in this way: a certain amount of effluent, truncated at both front and rear ends, but shaped according to the "Gaussian cone", travels down this cone at the speed u, and in this way exposes different places downstream from the source at different times. The time variation of σ_y and σ_z results from the wavering of the plume under the influence of eddies larger than the transversal plume dimensions. A subsection of the following is devoted to a discussion of the growth of these two parameters with time.

It should be mentioned that the Gaussian plume formula applies to a point source. If the source has a finite spatial extent, the resulting plume can be thought of as a sum of several point sources, but usually it is easier and sufficiently accurate to substitute the real situation by one in which there is one point source upstream with respect to the real source containing the whole source strength. The distance upstream is determined by the transversal dimensions of the real source. Having "travelled" from the fictitious point of release to the real source, σ_y and σ_z should be approximately equal to the transversal dimensions of the source.

5.2.2. The influence of averaging time on the time-mean concentrations

One of the characteristics of the Gaussian dispersion model with dispersion parameters σ_y and σ_z given as increasing functions of the distance x from the source is that the plume concentration will decrease with x. Very often the Gaussian plume is thought of as a cigar-shaped cloud which is constant with time. In general this picture is incorrect because - as easily appears from looking at the exhaust from a real stack - the plume will waver in time in both the vertical and the lateral direction with respect to the mean wind direction. However, for practical computations, this steady Gaussian plume model will generally give satisfactorily accurate results, provided that σ_y and σ_z are averaged over the specified time of interest. To explain why this is so, a brief qualitative discussion of plume kinematics is needed.

Consider a plume as being composed of a series of puffs as indicated in Fig. 5.1, where such a series is shown in an instantaneous or "frozen" picture. (In order to illustrate the general idea better, only a fraction of the total number of puffs is shown). Each puff is transported away from the source by the wind, and simultaneously it grows because of the action of turbulent eddies with linear dimensions less than or equal to its size. The technical term for this growth process is relative diffusion, and the growth rate is determined mainly by eddies of a size comparable to the puff itself. Statistically, the average puff size will be a function only of x for a given atmospheric situation. The average instantaneous plume can thus be characterised by the lateral and vertical root-mean-square widths σ_{oy} (x) and σ_{oz} (x) as functions of x.

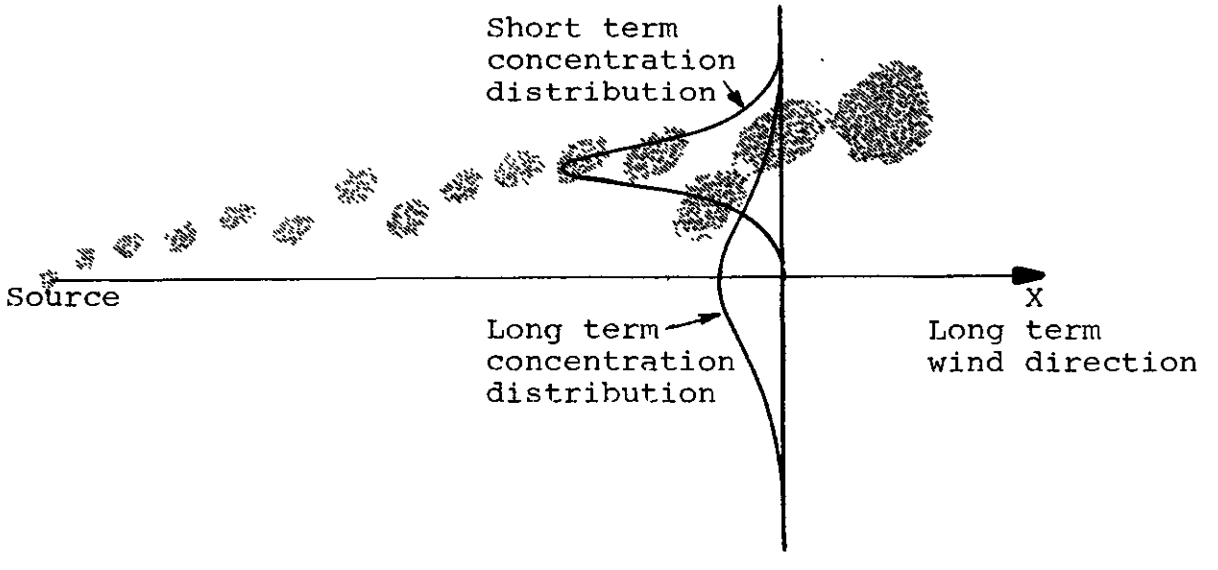


Fig. 5.1. Series of puffs.

As a puff moves with the wind, larger and larger eddies will take part in and be responsible for its growth. The eddies larger than the puff, on the other hand, will make it move around in a random fashion and give rise to the aforementioned wavering of the plume. At a particular distance x downstream from the source, and along an axis determined by the long-term wind direction, the puffs will pass a plane perpendicular to this direction with a randomly varying distance of their centres from the axis. For short-term averaging, the root-mean-square distance will be smaller than the corresponding long-term averaged root-mean-square distance. This is indicated in Fig. 5.1, where the short- and long-term distributions of the puff distances from the axis are shown. The long-term distribution has its maximum at the axis and is broader than the short-term distribution, the maximum of which is off the axis, in general. The root-mean-square widths of these distributions of distances from the axis are functions of both distance x and averaging time T. They are directly related to the concentration distributions, for which the total-root-mean-square widths are found by adding the root-mean-square distance and the root-mean-square puff size "by the squares" in both the vertical and the lateral direction. Expressed formally, the mathematical relations are

$$\sigma_y^2\ (x,T) = \sigma_{oy}^2\ (x) + \sigma_{1y}^2\ (x,T) \qquad (5.3a)$$

and

$$\sigma_z^2\ (x,T) = \sigma_{oz}^2\ (x) + \sigma_{1z}^2\ (x,T)\ , \qquad (5.3b)$$

where σ_{1y} (x,T) and σ_{1z} (x,T) are the root-mean-square horizontal and vertical distances from the axis at the distance x for the averaging time T.

Later a case in which the relative diffusion may be neglected will be discussed, but in general both this and the "random walk" contributions (σ_{1y} and σ_{1z}) must be considered. The relative importance of the two terms will change with x for a fixed T. The relative diffusion will become more and more important with increasing distance, because the puffs will grow and comprise larger and larger eddies in their growth, until in the last somewhat speculative stage all turbulence on all scales is involved in the relative diffusion. For distances shorter than several tens of the linear scale of the turbulence, dimensional arguments together with order-of-magnitude evaluations show that relative diffusion is unimportant if the averaging time is large compared with the Eulerian time scale. Under such circumstances several formulas have been suggested to relate root-mean-square width at one averaging time to that at another. The one chosen here is the same as used in Th 80, namely

$$\sigma_y\ (x,T) = \sigma_y\ (x,T = T_o) \times \left(\frac{T}{T_o}\right)^{1/3} \qquad (5.4a)$$

and

$$\sigma_z\ (x,T) = \sigma_z\ (x,T = T_o) \times \left(\frac{T}{T_o}\right)^{1/3} \qquad (5.4b)$$

where T is measured in seconds and T_o is equal to 1800 seconds.

5.3. Atmospheric parameters

Before plume formulas (5.1) or (5.2) can be used in a computer model, the wind direction and the actual magnitudes of Q, u, σ_y, σ_z and H have to be determined. The only parameters that are determined directly are the wind speed and direction. As mentioned before, the source strength Q used in (5.1) or (5.2) need not be the actual amount of material pouring out of the source during one unit of time. A factor reducing Q is introduced to account for losses resulting from deposition and radioactive decay. The atmospheric stability will influence both diffusion parameters σ_y and σ_z, as well as the effective height of release H. In this section the following meteorological parameters relevant to dispersion in the atmosphere will be discussed: precipitation and deposition, atmospheric stability, wind direction, wind speed, and mixing height.

5.3.1. Precipitation and deposition

Whether or not there is precipitation is of great importance for the rate of removal of pollutants from the plume. In the case of no precipitation the plume is diluted only because of deposition on the ground. For a definition of this concept see chapter 4. In this case the lower boundary of the plume is affected directly. When there is precipitation the interior of the plume will be diluted directly.

The efficiency of dry deposition depends largely on the wind speed and the turbulence intensity, but the physical, chemical, photochemical, and biochemical processes taking place at the surface when material is deposited are also of much importance. To a large extent these processes depend on the form of the pollutant, i.e. whether it is a gas or an aerosol and, in the latter case, what the particle sizes are. As deposition velocities depend strongly on the type of material to be deposited, the composition of the plume changes downstream in the sense that the ratios between the concentrations of the different constituents change with their distances from the source.

In the case of precipitation, there is wet removal of effluents. It is important to distinguish between below-cloud scavenging, or wash-out, and in-cloud scavenging, or rain-out. For wash-out, a removal rate or wash-out coefficient l_g (s^{-1}) is introduced usually (see eqs. 4.4 and 4.5). This is proportional to the precipitation rate; for gases it is a function of how close the concentration in the water drops is to the equilibrium concentration, and for aerosols a function of the aerosol and drop sizes. The latter could also be termed a collection efficiency. Also in the case of wash-out the plume composition changes downstream.

Rain-out refers to processes whereby material is removed from the plume to the droplets or condensation nuclei of the clouds, and where later a deposition can take place elsewhere with the rain from the cloud. Rain-out can cause completely unpredictable deposition patterns. On the one hand this can lead to a significant reduction of concentration in the plume, but on the other, to areas with increased contamination at larger distances from the source.

A quantitative description of this phenomenon would require as a minimum a good model for cloud dynamics, including condensation processes, in particular the effect of condensation nuclei.

It must also be realized that neglect of this phenomenon would lead to an overestimation of the predicted doses in the cases where rain-out would have taken place.

In the Gaussian model, dry deposition and wash-out are accounted for by source depletion. For dry deposition it means that Q is reduced with a distance-dependent factor, as though the plume was diluted with the same fraction through the entire cross section at that distance. This does not correspond to what is really taking place, because the effect of dry deposition must be greater on the concentration close to the ground than on that further away. However, the deposition is usually so small that the approximation is considered to be quite accurate. For wash-out, source depletion means that Q is reduced by both a space-dependent and a time-dependent factor, where the latter reflects the variation in precipitation intensity. This way of modelling the wet scavenging is in principle completely correct if the part of the plume being considered has horizontal dimensions smaller than those of the rain belt.

It should be borne in mind that if it is raining, wash-out is in general more efficient in diluting the plume than dry deposition. If we measure the efficiency of wash-out in terms of a deposition velocity, v_g will be about $\sigma_z l_g$, which is typically 0.03 m/s, but this can be as large as of the order of 1 m/s, whereas v_g for dry deposition is typically about 0.01 m/s or less.

5.3.2. Atmospheric stability

The stability of the atmosphere is an important concept for describing the dispersion conditions in the atmosphere. It can be illustrated by the following example: If a small parcel of air is moved upward (or downward), it will expand (or be compressed) because the pressure in the atmosphere decreases with height. As the volume of the parcel changes, so does its temperature, a decrease in temperature corresponding to expansion and vice versa. This type of thermodynamic process where no heat is transferred is called an adiabatic expansion (or compression) and the change in temperature which occurs can be computed if the variation of pressure with height is specified. In the lower atmosphere the temperature change with height for an adiabatic expansion is -1°C per 100 m altitude increase.

If the surrounding atmosphere has a temperature distribution that decreases with height at the same rate, the air parcels will be in equilibrium with each other. In this case the condition of the atmosphere is said to be <u>neutral</u>. Under situations of neutral stability, atmospheric turbulence appears only as a result of friction with the surface of the earth.

If the temperature in the atmosphere falls more than 1°C for a height increase of 100 m, a parcel which is moved upward will arrive at surroundings that are relatively colder. As the warmer parcel is lighter it will have a positive buoyancy and the upward movement will continue. If, on the other hand, the parcel is moved downwards it will arrive at surroundings that are relatively warmer, and the movement will therefore continue downward. Under such unstable conditions where each movement in the vertical direction is increased, a stronger turbulence results than in a neutral situation. If a condition like this prevails, the atmosphere is said to be <u>unstable</u>.

If the temperature in the atmosphere falls less than 1°C for a height increase of 100 m, or if the temperature rises with increasing height, it can be seen by arguments analogous to those above that turbulent motions will be counteracted. In such situations where buoyancy forces act to oppose vertical motions the condition of the atmosphere is said to be <u>stable</u>. In a stable atmosphere, the turbulence level is less than in the neutral atmosphere, and in a case of strong stability turbulent motions can be nearly eliminated.

The Risø measurements show that unstable, neutral, and stable atmospheric conditions occur for approximately 5%, 60%, and 35% of the time, respectively.

The stability conditions in the atmosphere have a strong influence on its dispersive ability. An appreciation of this fact can be gained by watching the visible behaviour of smoke in the atmosphere. It is well known that the smoke trail from a tall stack takes a variety of forms according to the weather conditions and the time of day. Neutral conditions are characterized by moderate wind speed and a thoroughly cloudy sky or high wind speed with or without clouds. During neutral conditions the smoke moves in a fairly straight well-defined trail which increases in width and height as the distance from the source increases. Unstable conditions are usually characterized by light winds together with sufficient sunshine to warm the ground surface. The smoke behaves in a very irregular fashion and the strongly disturbed air over the heated surface leads to a rapid spread in the vertical and to an erratic variation in the direction of travel of successive sections of the smoke plume; it rapidly reaches a stage where it is no longer visible. Stable situations occur more frequently at night when the wind is generally light and the sky sufficiently clear to result in an appreciable cooling of the ground. Vertical and horizontal spread is considerably reduced and the smoke moves downwind in compact visible form for appreciable distances, often not in a straight trail but rather like a meandering river.

The three categories described above constitute the simplest classification of diffusive conditions. In the literature the following terminology is often used:

Atmospheric conditions	Plume behaviour
unstable	looping
neutral	coning
stable	fanning

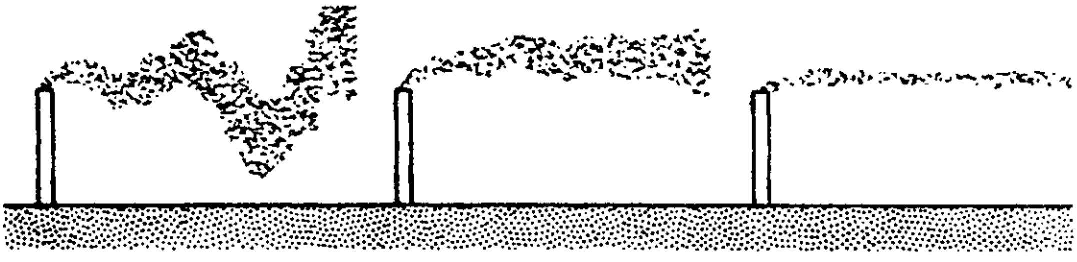


Fig. 5.2. The three characteristic plume forms.

Many years of measurement of wind speed, wind direction, and horizontal and vertical fluctuations of the wind direction, all at the effective stack height, yield the best set of single-point meteorological measurements for estimating climatological statistics for the atmospheric dispersion ability with regard to the stack under consideration. Measurements of wind direction fluctuations are rather intricate turbulence measurements and have rarely, if ever, been obtained on a climatological basis.

In practical diffusion calculations, meteorological specifications will often have to be in terms of the routine data available on mean wind speed and direction, and cloud cover or vertical temperature gradient.

5.3.3. Mean wind direction

The mean wind direction is an important parameter in defining the direction in which the plume is transported. The applicability of the Gaussian plume model requires a steady mean wind direction. A shift in the mean wind direction during a continuous release will result in a larger area being passed by various sections of the plume whereby the actual doses will be appreciably smaller than calculated.

5.3.4. Wind speed

The wind speed is directly important in determining the initial dilution because the initial volume of air containing the amount of material emitted in a given time must be proportional to the wind speed. However, wind speed also has an additional controlling influence on diffusion through its effect on turbulent mixing in the atmosphere. Turbulent mixing is also strongly influenced by the state of the sky through its control of the thermal stratification of the atmosphere.

5.3.5. Mixing height

Just as the vertical growth of a plume is limited by the presence of the ground, so can growth be limited from above. This is, for example, the case when the layer in which the plume is transported is of neutral stratification and has a stable layer aloft. The layer of the lower atmosphere in which free vertical plume rise and growth is possible is called the mixing layer. Its thickness is called the mixing height. The effect of a limited mixing height on vertical dispersion can be accounted for in the same way as the effect of the ground, i.e. by using an imaginary additional source in the mirror image with respect to the top of the mixing layer. Often a simpler approach is used where a uniform distribution of material in the vertical is assumed from a distance which is twice the distance where the mixing height equals the effective stack height plus twice the vertical dispersion parameter. In the intermediate area between this distance and that where the plume hits the top of the mixing layer, the concentrations may be obtained by interpolation.

5.4. Stability classes and dispersion parameters

In the foregoing discussion of the state of the atmosphere and its influence on the ability of the atmosphere to disperse a continuous release, three states (dispersion categories) were identified: unstable, neutral and stable. However, it is obvious that the atmosphere does not assume only these three easily identifiable states but that it displays a continuous spectrum of states. Nevertheless, because of the purely practical need to identify the dispersion ability of the atmosphere by means of routine meteorological measurements, a classification system is used that builds not on three but on seven discrete categories. This is the Pasquill system (Pa 61) which ever since its publication has been a basic reference system for nearly all dispersion calculations. It contains the following classes:

A extremely unstable
B moderately unstable
C slightly unstable
D neutral
E slightly stable
F moderately stable
G extremely stable

When a stability class is to be determined on the basis of routine measurements, a procedure established by Turner is often used (Tu 64). Stability is here determined by wind speed and a radiation index, the latter being determined by cloud coverage, cloud height, the time, and the geographical position of the meteorological station. The following diagram shows the connection between radiation index, wind speed and stability class. Intense incoming radiation corresponds to index = 4, and a negative index to outgoing radiation.

Wind speed	Radiation index						
m/s	4	3	2	1	0	-1	-2
< 2	A	A	B	C	D	F	G
2-3	A	B	C	D	D	D	F
3-5	B	B	C	D	D	D	E
5-6	C	C	D	D	D	D	E
6 <	C	D	D	D	D	D	D

Another method often used to determine the stability class is based on direct measurement of the vertical temperature gradient. It has been established that class A corresponds to a temperature decrease over 100 m of 1.9°C or more, and class F to an increase over 100 m of at least 1.5°C. The method is used where temperature is measured at several heights, such as on a meteorology tower, and where radiation is not measured.

Description	Category	T(100 m) - T(0) m
extremely unstable	A	< -1.9
moderately unstable	B	-1.9 to -1.7
slightly unstable	C	-1.7 to -1.5
neutral	D	-1.5 to -0.5
slightly stable	E	-0.5 to 1.5
very stable	F + G	> 1.5

The two methods rarely give exactly the same result: for a climate subject to maritime influence, the distribution of stability categories is often as appears in the following diagram.

Category	occurs in % of the time	
	Method 1 (radiation)	Method 2 (temperature gradient)
A, B, C	7	2
D	75	60
E	10	30
F, G	8	8

The usefulness of the above classification system lies particularly in the fact that, for each stability category, a certain variation of dispersion parameters with distance is prescribed. There are a number of different works dealing with the dependence of dispersion parameters on stability of which the best known is the Workbook of Atmospheric Dispersion Estimates (Tu 70). This is often used as a basic reference.

5.5. Meteorological statistics

An assessment of conditions in the area of the Sound from the viewpoint of meteorological dispersion in relation to the Copenhagen-Barsebäck problem, and a description of the dispersion model used (the Gauss plume model), are found in chapter 4 and appendix 3 of He 77. On this basis, 21 "weather situations", namely classes B and D with a mean wind speed of 10 m/s and class F with 5 m/s, were specified for a preliminary parameter study. In each class use was made of three values for the dry-deposition velocity (v_g = 0.5; 1.0 and 2.0 cm/s). In class D, a further three values were used for the wash-out coefficient ($l_g \cdot 10^5$ = 5, 10 and 20 s^{-1}) and in class F calculations were made both without meandering and with a meander factor of 4.

It appeared from this parameter study that the weather situations that could be unfavourable for Danish territory in the event of a serious accident at Barsebäck can reasonably be assumed to lie in classes D and F.

A further investigation of reasonable, but pessimistic, values for wet and dry deposition parameters (chapter 4) then led to the specification of five "weather situations" for the final parameter study in chapter 7. It appears from the calculations in chapter 7 that of the five situations selected, only D and F are of interest. Both these were investigated individually in He 77, but because of their importance for the present investigation they have been analysed further.

5.5.1. Extremely stable weather situations

Considering a plume that spreads in a very stable atmosphere, it can be observed that its thickness σ_z varies only slowly with distance from the source. The plume can often be seen over a distance of many km and at times it has large, horizontal meanders. These result from large, two-dimensional eddies which, because the stable atmosphere lacks the ability to produce new turbulence, represent the remains of the original turbulence. The eddies are transported with the wind in the direction that this takes, and thus meandering occurs. Meandering means that the temporal mean value of the concentration of the smoke at a given spot downstream of the source can be considerably less than the immediate value.

The phenomenon can be expressed quantitatively by means of equation (5.3a), as the occurrence of meandering means that while $\sigma_{0y}^2(x)$ is constantly relatively small, $\sigma_{1y}^2(x,T)$ will increase rapidly with T and thus usually be the dominant part for release times T of one hour or more.

An attempt was made in He 77 to assess the possible existence and effect of meandering, based on data measured both over land and over water. The conclusion was reached that an increase of the horizontal dispersion by a factor 4 to 6 relative to Pasquill-Gifford (Tu 64) seems realistic under stable conditions with little wind, and for an averaging time of three hours.

This effect was not included in the dose calculations in the former report, as meandering gives a reduction of the largest individual doses. On the other hand, the parameter study in chapter 7 shows that category F with a meander factor gives the most serious consequences associated with land contamination.

As is to be expected from the above qualitative considerations, meandering usually occurs in connection with low wind speeds. Thus the investigation in He 77 comprised wind speeds of between 1 and 3 m/s; in IAEA 80 it is recommended that use be made of a meander factor of 4 for speeds below 2 m/s. It is, however, a question whether there exists an upper wind speed above which meandering does not occur. This problem is analysed in Kr 81, which gives a theoretical treatment of the subject of meandering and analyses relevant data.

The result is that horizontal dispersion in a stable atmosphere under certain simple assumptions is given by an expression very similar to Taylor's diffusion theorem. Assuming an exponential shape for the Eulerian and Lagrangian correlation function, an expression is obtained where the horizontal dispersion parameter σ_y is given as a function of:

- x distance from source to measuring-point (m)
- T averaging time (s)
- u mean wind speed in the direction of the mean wind vector (over the time T) ($m\ s^{-1}$),
- σ_v^2 the variance of the component of the wind vector at right angles to the mean wind direction ($m^2\ s^{-2}$)
- T_L the Lagrangian time scale that is a characteristic time for the large eddies (s)
- T_E the Eulerian time scale that is a characteristic time for the atmospheric movements observed from the release point (s),

making further assumptions relating to the Lagrangian and Eulerian time scales.

The data analysis was carried out on data measured along Risø's meteorology tower during the period 1976 to 1978. The result is visualized in fig. 5.3, where σ_y (m) at a distance of 20 km is calculated on the basis of measurements and plotted against the mean wind speed. As expected, the points are somewhat scattered, but it is obvious that σ_y is a decreasing function of wind speed. The regression line introduced gives

$$\sigma_y(20\ \text{km}) = 5400 \times u^{-0.8} \qquad (5.5)$$

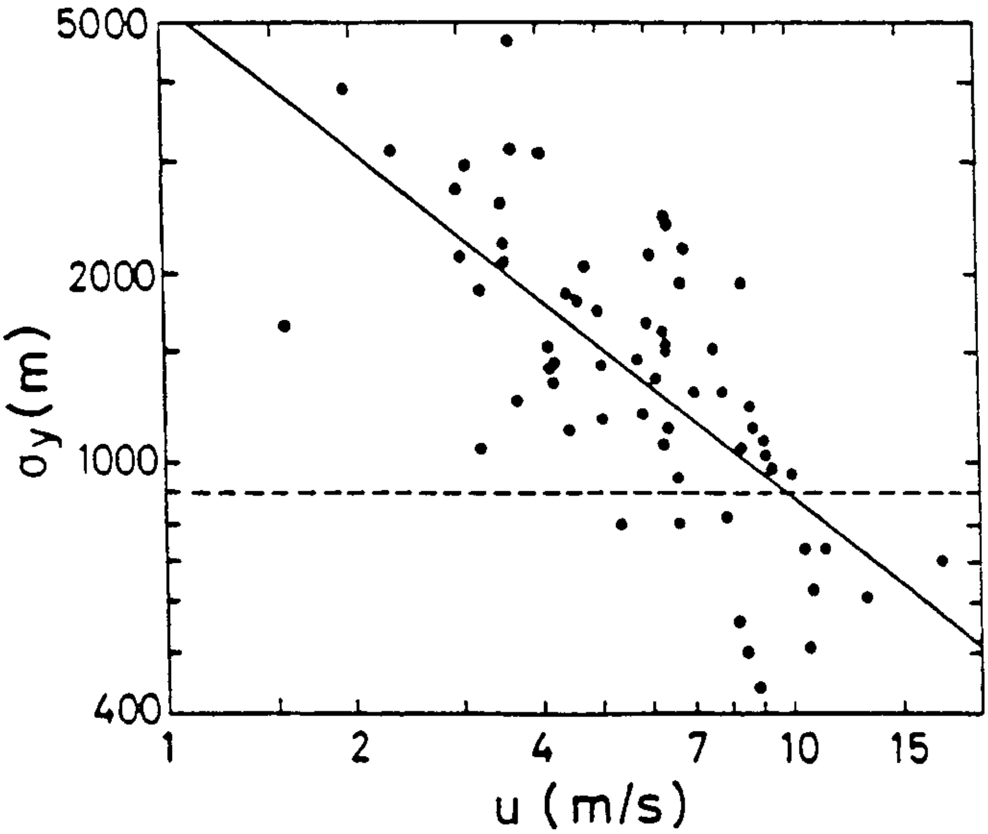


Fig. 5.3. Plot of σ_y against u for a distance from the source corresponding to 20 km and an averaging time of three hours. The magnitude of σ_y is calculated by means of Risø data from the period 1976-78. The unbroken line represents $\sigma_y = 5400 \times u^{-0.8}$. The dashed line gives σ_y from Turner's Workbook, Tu 70, corrected for a time-averaging over three hours.

The calculations in chapter 7 make use of σ_y from Turner's Workbook, which at a distance of 20 km from the source gives a value of 500 m. This is corrected in the calculations for an averaging time of 3 hours, corresponding to the release time of a BWR-2 accident. The correction factor is given by $(T/T_o)^{1/3}$, where T is three hours and T_o half an hour. The corrected value for σ_y is then 900 m. This value is drawn as a dashed line on the figure. The meandering factor used in some of the calculations in chapter 7 is set equal to 4, corresponding to $\sigma_y(20)$ = 2000 m. For the selected wind speed of 5 m/s, this σ_y lies above the regression line that gives σ_y = 1600 m.

To determine whether dispersion over water in stable situations follows the same pattern as found in the foregoing for dispersion over land, two years of data (1978-1979) from a 70 m high meteorology tower on the island of Sprogø were analysed. σ_y(20 km) was again used as an example, calculated and plotted against the wind speed (fig. 5.4). Just as the Risø data, the Sprogø data seem to indicate that σ_y is a decreasing function of wind speed. The regression line has the form:

$$\sigma_y(20\ \text{km}) = 6000 \times u^{-0.6} . \qquad (5.6)$$

Apparently, σ_y over water under stable conditions is larger than it is over land. The scatter of points around the regression lines indicates, however, that it would be reasonable to adopt one formula only that covers both land and water.

For the Sprogø data, a further calculation was made of σ_y at the distances 10, 20, 30, 40, 60, 80, 100 and 120 km for the wind speeds 1, 2, 4, 8 and 16 m/s. The result is shown on fig. 5.5 together with, respectively, σ_y uncorrected, σ_y time-average corrected and σ_y meander corrected by a factor 4. As mentioned above, the last σ_y curves are used in the calculations in chapter 7 together with a wind speed of 5 m/s. This combination of parameters seems to be in good agreement with the σ_y values calculated on the Sprogø data.

For the Risø data, the analysis showed that stable periods of special relevance to the present work occur approximately 30 times a year, while the Sprogø data show a frequency that is twice as large. Making a further assessment based on the Sprogø data of the probability that, at an arbitrary point in time, a stable period will occur, which then lasts at least 3 hours, the probability is found to be approximately 1.2% without discriminating for direction. If, further, one imposes the condition that the wind must blow from a 90° sector around east, this probability is reduced to approximately a fifth (~ 0.25%).

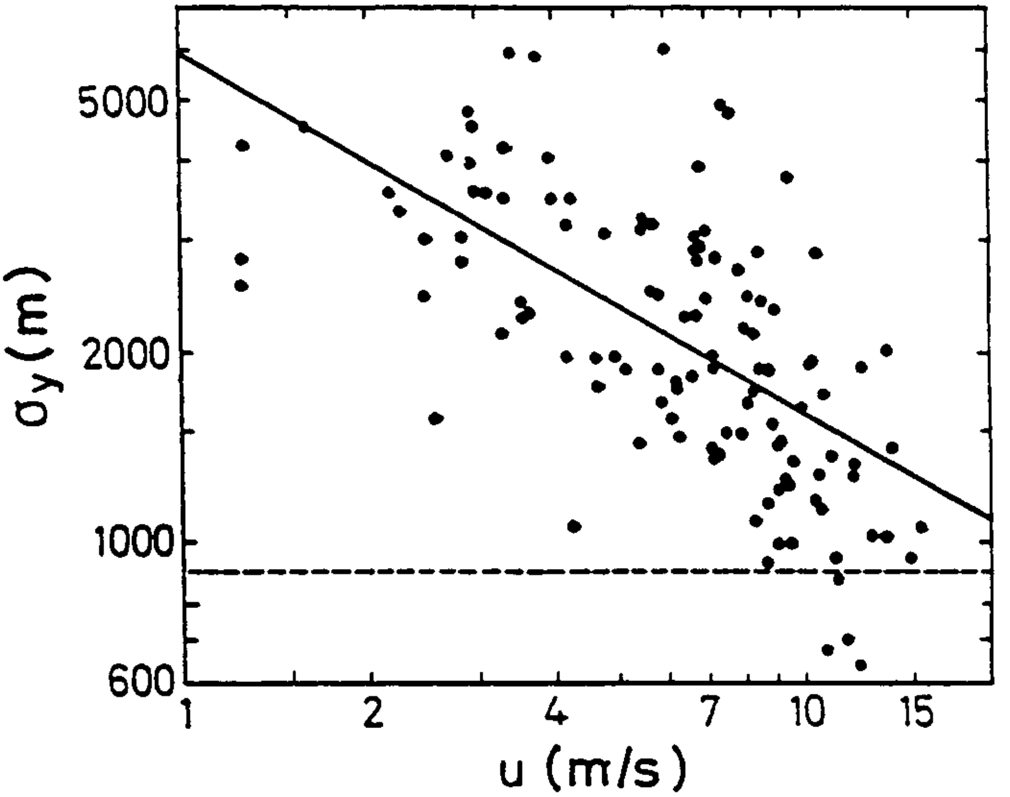


Fig. 5.4. Plot of σ_y against u for a distance from the source corresponding to 20 km and an averaging time of 3 hours. The magnitude of σ_y is calculated by means of Sprogø data from the two-year period 1978-79. The unbroken line represents $\sigma_y = 6000 \times u^{-0.6}$. The dashed line indicates σ_y from Turner's Workbook, Tu 70, corrected for a time-averaging over 3 hours.

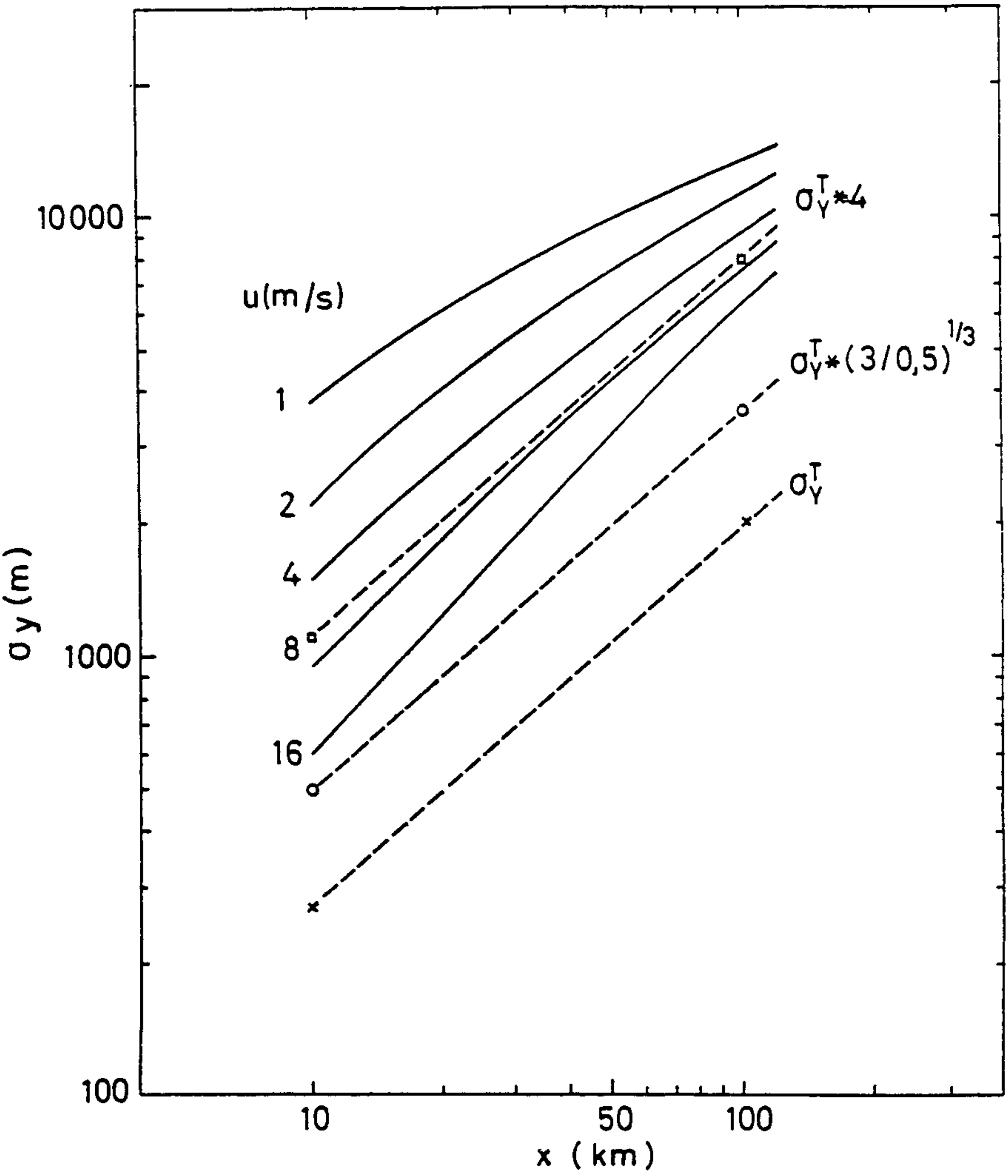


Fig. 5.5. Plot of σ_y against the distance from the source for wind speeds 1, 2, 4, 8 and 16 m/s and an averaging time of 3 hours. The dashed lines represent, respectively, σ_y from Turner's Workbook, Tu 70, (σ_Y^T) and these values corrected for time averaging by a factor $(3/0.5)^{1/3}$ and meandering by a factor 4.

5.5.2. Weather situations with precipitation

In the parameter study in chapter 7, the neutral weather situation (D) with precipitation appears as a situation that could be unfavourable for Danish territory in the event of a serious accident at Barsebäck.

Using a measuring series from St. Hareskov covering 23 years (1951-1973) the probability was assessed of a certain amount of precipitation falling within a given period of time. The result appears in table 5.1, which gives the accumulated function of the period under consideration with a temporal resolution of an hour. As an example, the probability of less than 2 mm of rain per hour over three hours is 99.7%, and of less than 1 mm falling in the same period of time 98.5% - which implies that the probability of between 1 and 2 mm of rain falling per hour during a time interval of 3 hours is 1.2%. The interval 0.1 mm contains the probability for an amount of precipitation less than or equal to 0.1 mm, for which reason this interval contains all situations without precipitation.

As discussed earlier, wet deposition is parameterized in terms of the rain intensity which is kept constant during the calculations in the dispersion model used. In so far as the assumption of constant rain intensity over the whole area affected in the course of the accident is reasonable, the statistics given above are relevant.

5.6. Choice of meteorological parameters for the dose calculations

The meteorological parameters included in the dose calculations cannot be chosen independently of one another if the situations modelled are also to be physically possible. On the other hand, the stability classification schemes (section 5.4) give a very simplified picture of the possible dispersion situations. For example, the wind speed in one of the methods (that of Turner) is limited to a certain interval in each class, while the classes in the other method are independent of wind speed. Both hours →

accumulated probability (o/oo)

precipitation intensity (tenths of mm/h) →

	1	2	3	4	5	6	7	8	9	10	11	12	
51	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	51
50	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	50
49	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	49
48	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	48
47	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	47
46	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	46
45	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	45
44	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	44
43	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	43
42	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	42
41	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	41
40	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	40
39	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	39
38	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	38
37	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	37
36	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	36
35	998	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	35
34	998	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	34
33	998	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	33
32	998	999	999	1000	1000	1000	1000	1000	1000	1000	1000	1000	32
31	998	999	999	999	1000	1000	1000	1000	1000	1000	1000	1000	31
30	998	999	999	999	1000	1000	1000	1000	1000	1000	1000	1000	30
29	997	998	999	999	1000	1000	1000	1000	1000	1000	1000	1000	29
28	997	998	999	999	999	1000	1000	1000	1000	1000	1000	1000	28
27	997	998	999	999	999	1000	1000	1000	1000	1000	1000	1000	27
26	997	998	999	999	999	999	1000	1000	1000	1000	1000	1000	26
25	996	998	998	999	999	999	999	1000	1000	1000	1000	1000	25
24	996	997	998	999	999	999	999	999	1000	1000	1000	1000	24
23	996	997	998	998	999	999	999	999	999	1000	1000	1000	23
22	995	997	997	998	999	999	999	999	999	999	1000	1000	22
21	995	996	997	998	998	999	999	999	999	999	999	999	21
20	994	996	997	997	998	998	999	999	999	999	999	999	20
19	994	995	996	997	998	998	999	999	999	999	999	999	19
18	993	994	995	996	997	998	998	999	999	999	999	999	18
17	992	994	995	996	997	997	998	998	999	999	999	999	17
16	991	993	994	995	996	997	997	998	998	998	999	999	16
15	990	992	993	994	995	996	997	997	998	998	998	999	15
14	989	991	992	993	994	995	996	996	997	997	998	998	14
13	957	989	991	992	993	994	995	996	996	997	997	997	13
12	986	987	989	990	991	992	993	994	995	995	996	997	12
11	984	985	987	988	990	990	992	993	994	994	995	995	11
10	982	983	985	986	987	988	989	990	991	992	993	994	10
9	979	980	982	984	985	986	987	988	989	990	991	992	9
8	976	977	979	980	981	982	984	984	985	986	987	989	8
7	973	973	974	975	976	978	979	980	981	982	983	984	7
6	969	968	96[illegible]	969	971	972	973	974	975	976	977	978	6
5	964	962	961	962	962	963	964	965	966	967	969	970	5
4	958	954	953	952	952	952	953	953	954	955	956	957	4
3	951	944	941	939	937	936	936	936	936	936	935	936	3
2	940	931	924	920	916	913	911	908	907	906	904	903	2
1	924	918	897	888	880	874	867	862	857	852	848	844	1
	1	2	3	4	5	6	7	8	9	10	11	12	

Table 5.1. The table gives the accumulated probability for in a certain period of time to experience less or equal a given average precipitation intensity.

methods are results of attempts to describe the average states in the lowest hundreds of meters of the atmosphere. Therefore, it is not uncommon to find individual situations that cannot be classified immediately according to one or the other method. Thus, the turbulent structure can very well correspond to class A or F, even though the wind speed is greater than 3 m/s, in contrast with the rules for Turner classification. Likewise, the situation can well differ from that corresponding to D, even though the wind speed is greater than 6 m/s and the sky overcast (radiation index 0), for example, in the case of cold air advection (i.e., a cold air mass is carried in above a warm surface). The temperature gradient classification method offers corresponding problems. Common to both methods is the fact that they often give a reasonable statistical distribution of the weather situations over the different stability classes but, when used in individual situations, they can easily apply to several classes beside the dispersion situation actually existing.

These problems imply that in parameter studies one often wishes to select individual situations that fall outside the allowed variation areas in the classification schemes. Thus, in chapter 7 the choice falls on category B with a wind speed of 10 m/s.

5.6.1. Deposition

Also what deposition is concerned, there are characteristic values for the parameters in the different dispersion classes. In class D precipitation often occurs in connection with longer periods of rain fronts, while in the unstable classes precipitation is generally of short duration and associated with scattered showers. In the stable situations the vertical movements in the atmosphere are strongly suppressed, for which reason the occurrence of significant precipitation in classes F and G is very improbable.

A large deposition velocity implies that a large amount of material in the plume is deposited close to the source, which is, of course, an advantage for areas far from the source. A small deposition velocity, on the other hand, results in larger doses far from the source because the plume can transport the material released over longer distances without much depletion.

Thus it is impossible in general to give definite, pessimistic estimates for deposition parameters. However, for a given set of dispersion parameters, the deposition velocity giving the greatest contaminated area can be found (Je 80).

This deposition velocity is not, however, always physically realistic because it represents an upper limit to the velocity of dry deposition given by the product $u(u_*/u)^2$ of the square on the intensity of the turbulence and the wind speed. In class B the intensity of the turbulence will be typically 0.06 and the speed 2 m/s, for which reason the dry deposition velocity will be less than 0.7 cm/s. In class F the intensity of the turbulence is small, less than half of the above; for this reason the dry deposition velocity will often be less than 0.2 cm/s. For larger wind velocities these upper bounds on the deposition velocity increase correspondingly.

In practice, the dry deposition velocities are often significantly smaller than the values given above because the surface is not a perfect absorber but shows a resistance to absorbance (cf. chapter 4).

The rate of wet deposition is only limited by the intensity of the precipitation. The greater the intensity, the greater the wash-out. For a gas, the effect of wash-out depends on the solubility of the gas in water and a characteristic time for the dissolution process. En 68 gives the following values for the wash-out coefficient l_g for a very active gas, e.g., bromine:

Intensity of precipitation (mm/h)	0.06	0.1	0.5	1	3	10	100
Wash-out coefficient (1/s) × 10^5	1	1.3	3	4	10	20	100

Gaseous iodine is less active than bromine, and for free iodine the deposition parameter is about two orders of magnitude less than the values shown above. The deposition parameter falls a further two orders of magnitude for CH_3I (Ni 81).

With regard to the wash-out of particles, the efficiency of the process depends on particle size and the distribution of the size of the rain drops. In the calculations, however, use is made of the same values for the deposition parameter as given above. This can be justified on the basis of the existence of an empirical relation between the sizes of rain drops and the intensity of precipitation, as well as on the fact that all the relevant particles are about one micrometer in size.

5.6.2. Choice of weather situations for the parameter study

Chapter 7, fig. 7.2, shows the five weather situations selected for the parameter study. The choice was based partly on the above considerations and partly on the results published in He 77. The calculations in chapter 7 show that the most unfavourable of these situations should be sought within the extremely stable ones (category F). The present section gives a discussion of why the most unfavourable weather situation is characterized by class F with meandering, a wind speed of around 5 m/s and a dry deposition velocity of between 1 and 2 cm/s.

The calculations in chapter 7 show that the velocity of dry deposition v_g has much influence on the resulting contamination. Let m_s define a limit value for deposited amount per unit area, m, under which an area is not considered to be contaminated. If the deposition velocity is large, the plume is diluted rapidly, the largest amounts are deposited close to the source and the distance from the source, where $m < m_s$, is short. In contrast, if v_g is small, the distance to the point where $m < m_s$ will be large, and the contaminated area will be large. If v_g gets very small, m may not reach the value m_s anywhere. Thus it appears that there must be a value v_g^{max} that gives the greatest contaminated area (Roll's theorem).

Applying a number of simplifying assumptions, an expression is derived in Je 80 for determining the deposition parameter that gives the greatest contaminated area for a given set of dispersion parameters. The deposition parameter d is expressed by:

$$d = \frac{v_g}{\alpha u} , \tag{5.7}$$

where α stands for the vertical dispersion angle of the plume. The determination of v_g^{max} requires the specification of m_s, α and u, as well as of:

- M the total amount of activity released
- H the effective release height, and
- β the horizontal dispersion angle.

For high wind speeds, H is equal to the physical source height and for neutral conditions $\beta \sim \alpha \sim 1/33$, independent of wind speed. For low wind speeds and stable conditions, H and β are, however, functions of u. Taking plume lift into account and making use of Brigg's formula, gives $H \sim (1/u)^{0.33}$, and the investigation of meandering shows (figs. 5.3 and 5.4) that $\beta \sim (1/u)^p$, where p has a value of around 0.6 to 0.8.

Using the results of Je 80 and Kr 81, connected values for u and v_g^{max} in stable weather situations can be found. The result appears in fig. 5.6. It may be concluded that the determination of v_g^{max} depends only little on the choice of contamination level, and moreover that v_g^{max} must be sought among the values usually used for v_g, i.e. between 0.5 and 2.0 cm/s (although from a physical point of view these values are rather large). Calculations and arguments are as follows:

The total amount of activity released, M, is put at 264 MCi, corresponding to a BWR-2 accident.

With regard to the limit value for deposited amount per unit area, m_s, two examples are given: $m_s = 10^{-4}$ Ci m^{-2}, corresponding to approx. 0.7 rem over the first month, and $m_s = 4.2 \cdot 10^{-3}$ Ci m^{-2}, corresponding to approx. 30 rem over the first month. The horizontal dispersion angle β of the plume is determined by $\beta = \sigma_y/x$, where σ_y is given by $\sigma_y = 5400 \times u^{-0.8}$ (fig. 5.3) and the distance x is 20 km.

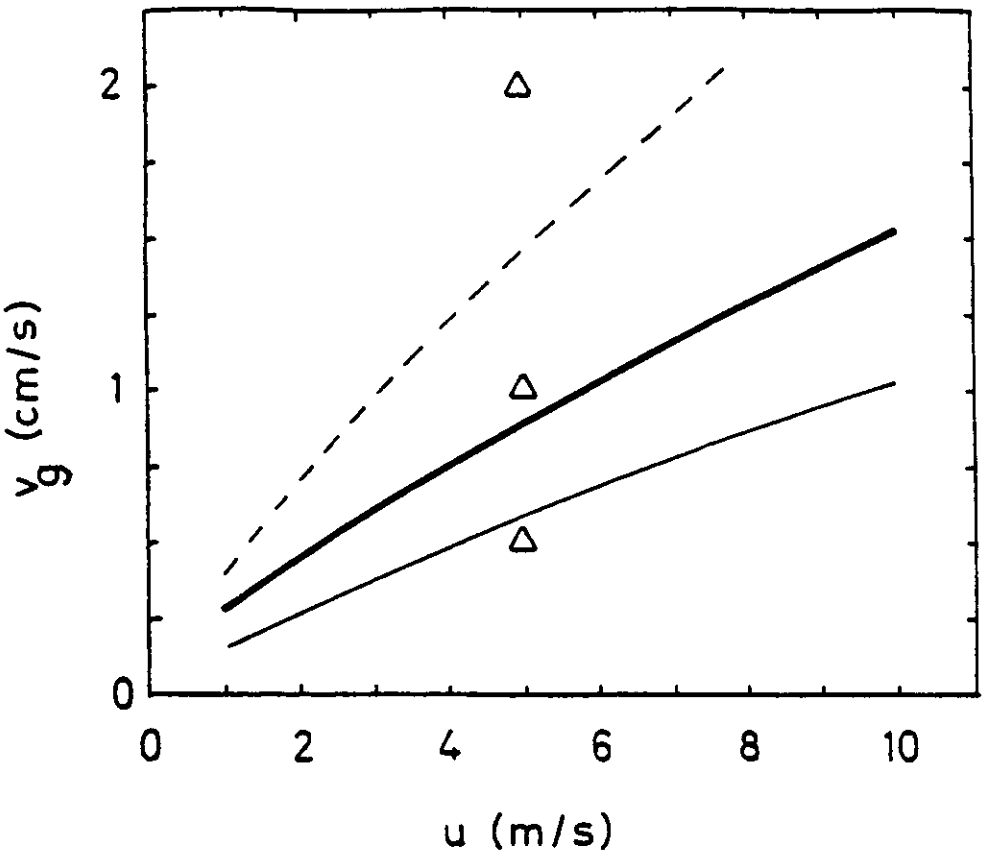


Fig. 5.6. The curves represent the deposition velocity v_g^{max} that, for a given wind speed, gives the largest possible contaminated area. The curves are calculated for a BWR-2 accident under stable conditions taking into account the meandering effect. The difference between the two unbroken curves is that the thin line is calculated for a contamination boundary of 10^{-4} Ci m^{-2} (~ 0.7 rem in the first month) while the thick line is calculated for $4.2 \cdot 10^{-3}$ Ci m^{-2} (~ 30 rem in the first month). Both are calculated for stability F. The dashed curve is analogous to the thick-line curve with the exception that stability E is used. The points Δ represent the cases used in the preliminary parameter study (21 situations).

The vertical dispersion angle α of the plume is put at 1/200, corresponding to class F, and at 1/100, corresponding to class E.

The source height is determined using Brigg's formula (cf. He 77) for plume lift under stable conditions. Use is made of $H = 2.9\ (B/(uS))^{1/3}$, where B is a measure of the initial over-temperature of the plume relative to the surrounding air, and S is the square of the so-called Brunt-Vaisàlà frequency and a measure of the stability of the atmosphere (the physical source height is neglected in these examples). If an S is used that corresponds to a temperature gradient in the atmosphere of 2.75°C per 100 m (stable weather situation with small to moderate wind speeds) and a B corresponding to a BWR-2 accident, then for u = 1 m/s we find a source height of 116 m (He 77, table 7). For other wind speeds, the source height is calculated from $H = 116/u^{1/3}$.

From Je 80 we find:

$$\frac{1}{d_m}\ (e^2)^{1/d_m} = \frac{\alpha}{2e}\ \frac{M}{m_s}\ \frac{\alpha^2}{\beta H^2} \tag{5.8}$$

which can be solved for d_m as a function of u. As d_m is defined as $v_g^{max}/(\alpha u)$, it follows that the deposition velocity which, at a given speed, gives the largest contaminated area can be calculated. As mentioned earlier, the result is given in fig. 5.6.

In spite of the fact that the right-hand side of the above equation varies somewhat with variations in β and H, and thus with variations in u, d_m varies only from 0.3 to 0.2 when u varies from 1 m/s to 10 m/s (α = 1/200, $m_s = 10^{-4}$ Ci/m^2). Similarly it can be ascertained that d_m is relatively insensitive to variations in, e.g., m_s and α. This shows that v_g^{max} is largely proportional to u. From fig. 5.6 it appears that v_g^{max} corresponding to u = 5 m/s should be set equal to approx. 1 cm/s. Consequently this preliminary study with the dose model made use of u = 5 m/s and v_g = 0.5; 1.0 and 2.0 cm/s as well as a factor of 1.81 (time-averaging) or 4 (meandering) on σ_y.

Should lower wind speeds be chosen, then v_g^{max} should be decreased correspondingly. The lower curve on fig. 5.6 largely represents physically possible deposition velocities, with the exception perhaps at the low end. This is because v_g will always be less than u_*^2/u, which can be extraordinarily small under very stable circumstances (u_* is a characteristic wind speed scale near the surface of the earth). To stay on the curve in fig. 5.6 at low wind speeds, i.e. to maximise the contaminated area, it will therefore be necessary to assume a certain wash-out effect. Stable weather situations of the type class F with low wind speeds are found in connection with intense long wave (infrared) radiation from the surface of the earth, and thus a predominantly cloudless sky. Therefore it is rather improbable that precipitation would occur under such a weather condition; for this reason stable weather situations with very low wind speeds will not be among the most serious in connection with an evaluation of land contamination.

As to precipitation, it can furthermore be ascertained that wash-out generally gives too high deposition velocities, far more than 2 cm/s, for situations with rain to be serious from the viewpoint of land contamination. The doses resulting from these situations (which are characterized as class D with rain) can be high, but they occur within a limited area.

Finally, for neutral and unstable conditions without precipitation the atmospheric dispersion of the plume is too rapid to give a contaminated area as large as for the class F situation.

5.7. References

En 68 Engelmann, R.J., 1968, "The calculation of precipitation scavenging". In: Meteorology and Atomic Energy, edited by D.H. Slade, USAEC Technical Information Center, Oak Ridge, Tennessee, 208-221.

Gi 68 Gifford, F.A., Jr., 1968, "An outline of theories of diffusion in the lower layers of the atmosphere". In: Meteorology and Atomic Energy, edited by D.H. Slade, USAEC Technical Information Center, Oak Ridge, Tennessee, 65-116.

He 77 Hedemann Jensen, P. et al., 1977, "Calculation of the individual and population doses on Danish territory resulting from hypothetical core-melt accidents at the Barsebäck reactor", Risø report 356.

IAEA 80 IAEA, 1980, "Atmospheric Dispersion in Nuclear Power Plant Siting": A Safety Guide, No. 50-SG-S3, IAEA Safety Guides.

Je 80 Jensen, N.O., 1980, "The simple approach to deposition". Proceedings of "Radioactive releases and their dispersion in the atmosphere following a hypothetical reactor accident", Risø, 22-25 April 1980. CEC, Luxembourg, Vol. 1, 331-343.

Kr 81 Kristensen, L., Petersen, E.L. and Jensen, N.O., 1981, "Lateral dispersion of pollutants in a very stable atmosphere. - The effect of meandering". Atmospheric Environment, 15, 837-844.

Ni 81 Nielsen, O.J., 1981, "A literature review on radioactivity transfer to plants and soil". Risø-R-450.

Pa 61 Pasquill, F., 1961, "The estimation of the dispersion of windborne material", Met. Mag., 90, 33.

Th 80 Thykier-Nielsen, S., 1980, "The Risø model for calculating the consequences of the release of radioactive material to the atmosphere", Risø-M-2214.

Tu 64 Turner, D.B., 1964, "A diffusion model for an urban area", J. Appl. Meteor., 3, 83-91.

Tu 70 Turner, D.B., 1970, "Workbook of Atmospheric Dispersion Estimates", Environmental Protection Agency, North Carolina.

6. NATURAL REDUCTION OF DOSES

Calculations of the dose rate from activity deposited on surfaces make use of a reference dose rate at a distance of 1 m above an infinite plane smooth surface with uniformly distributed surface activity. The actual dose rate will always be smaller than the reference dose rate as a result of different reduction factors, such as the shielding provided by structures and vehicles, the routine ploughing of agricultural land, and the influence of the weather on deposited activity, etc.

This chapter describes how these reduction factors can be evaluated and presents the factors that are used in the calculations in this report. However, it must be emphasized that these reduction factors do not assume the implementation of any special measures. Dose reduction that can be achieved by means of special action, hereunder alterations in the daily life of the population, are dealt with in chapters 8 and 10.

6.1. Structure shielding

6.1.1. Shielding factor

The shielding factor for a given structure and for a given radiation field is defined as the ratio between the dose rate from the radiation field with shielding and the dose rate (reference dose rate) without shielding. In the literature the shielding factor is also called the transmission factor.

The shielding factor for a given structure is described as the relation between the dose rate 1 m above the floor inside this structure - which originates from all sources of activity on roads, roofs and walls - and the dose rate 1 m above a plane, infinite, surface source having the same surface concentration:

$$S = \frac{\sum_i \dot{D}}{\dot{D}(\infty)}$$

6.1.2. Calculated shielding factors for dwellings in metropolitan Copenhagen

A mathematical model, implemented as a computer program (He 82), was developed to calculate the shielding factors for different types of building. The dose rate inside the structure, originating from the activity deposited on roofs, walls and roads, respectively, was calculated by means of numerical integration over all surface sources. Attenuation and build-up in air as well as in all the building materials are taken into account, and the dose rate is given by:

$$\dot{D} = \text{const.} \cdot \sum_{\substack{\text{all} \\ \text{sources}}} \int_y \int_x \frac{B(\Sigma\mu t)}{4\pi r^2} \cdot e^{-\Sigma\mu t} \, dx \cdot dy$$

Calculation of the shielding factor necessitates knowledge of the elemental composition of walls, floors, dividing walls and roofs to be able to determine the linear attenuation coefficient μ for the materials. The linear attenuation coefficient specifies the shielding ability of a material, as a material thickness of $1/\mu$ reduces the primary flux density from the gamma radiation source by 63%.

The report He 80 contains calculations of the shielding factor for different types of building. These calculations were based on information given by the National Building Research Institute regarding the representative dimensions of multistorey buildings and free-standing houses in the metropolitan area of Copenhagen, and on assumptions regarding the representative of such buildings in relation to roads, gardens, etc. Both for free-standing houses and for multistorey blocks, the moderate shielding afforded by windows, which are assumed to cover 25% of the area of outer walls, is taken into account.

In calculating the shielding factors, it is assumed that the activity deposited on the roofs and walls of free-standing houses and multistorey blocks is ten times less per unit area than on gardens.

For free-standing houses, the shielding factor is found to be approximately 0.07, corresponding to a reduction factor of 15 of the outdoor dose rate from an infinite surface source having the same deposition as the gardens surrounding the houses. For multistorey buildings, the largest reduction is found in the buildings of greatest height, and here for the appartments on the middle floors. In this case the outdoor dose rate from an infinite surface source having the same deposition as on houses and roads is reduced by a factor of up to 100 (shielding factor 0.01). For smaller buildings, the shielding factor for appartments on the middle floors is about 0.02, whereas in all cases the apartments on the bottom and top floors give poorest protection, corresponding to a shielding factor of 0.03-0.05.

In very large buildings, and in windowless cellars, a shielding factor can be achieved of one or two orders of magnitude less, i.e., 0.0001-0.005.

Experiments have been carried out in the USA to determine the shielding factor for houses, primarily for free-standing, one-storey or two-storey houses (Au 59, Bu 66, Bu 70). In order to simulate a homogeneously distributed surface source on the ground and on the roof, use was made of a tube system placed around the house and on the roof; a relatively strong radioactive source was pumped through the tubing at a constant rate. Integrating dosimeters were set up in the different rooms in the house to measure the dose from the rotating source. These experiments were intended to clarify the shielding effect of typical American houses in the event of fallout from nuclear weapons, and to determine whether this effect could be improved by simple means.

For houses built of brick or concrete blocks, reduction factors in the range of 5-10 were found away from doors and windows in the outer rooms. In inner rooms, reduction factors of 10 to 20 were found (Bu 66). Taking into account the differences between building traditions and standards in the USA and in Denmark, there is reasonably good agreement between the experimental results and the calculations used in the present study.

6.1.3. Weighted and time-averaged shielding factors for homes in the metropolitan area

For a given distribution of buildings, the weighted shielding factor can be calculated from:

$$\overline{S} = \sum_i p_i \cdot S_i$$

where p_i is the fraction of a given type of building having the shielding factor S_i. The weighted shielding factor expresses the ratio between the average individual dose rate for the area under consideration in the case that individuals remain indoors, and the dose rate for the same area in the case that individuals remain out of doors on an infinite surface.

Denmark's Bureau of Statistics provided information (DA 77) on the distribution of homes in the municipalities of the metropolitan area. Using this distribution and the calculated shielding factors for different types of house, calculations were made of the weighted shielding factors shown in table 6.1 (He 80).

It should be noted that for the urban municipalities (marked by *) a reduction of a factor 10 was introduced into the calculation. This was done to account for the fact that deposition on hard surfaces (of houses and roads) is a factor 10 less (see chapter 4) than on the grass-covered surfaces used as reference for the dose calculations in this report. Technicalities relating to the calculation procedure necessitated this step because the present dose calculation model does not take into account any spatial variation of the deposition velocity. The method used can only be regarded as an approximation, which in this case is reasonably good because there is a limited depletion of the plume as a result of dry deposition within the area subjected to the major part of the collective dose.

Table 6.1. Weighted shielding factors for homes in different municipalities.

Municipality	Shielding factor (%)
Copenhagen*	0.430
Frederiksberg*	0.359
Ballerup	3.78
Brøndby*	0.707
Gentofte	3.68
Gladsaxe	3.58
Glostrup*	0.985
Herlev	4.64
Albertslund	4.89
Hvidovre	3.64
Høje Tåstrup	4.67
Ledøje-Smørum	7.58
Rødovre	3.93
Ishøj	3.61
Tårnby	4.32
Vallensbæk	5.16
Greve	6.46
Gundsø	7.57
Køge	5.13
Ramsø	7.59
Roskilde*	1.13
Solrød	6.32

* indicates that the shielding factor includes a factor 10 to correct for the lower deposition velocity in urban areas (see the text).

To be able to calculate realistic doses, it is necessary to use a time-averaged shielding factor that takes into account the fact that the population is located partly out of doors and partly indoors in different areas. The time-averaged shielding factor, which expresses the ratio between the (average individual or collective) dose over a certain time period for a combination of indoor and outdoor location and the dose over the same time period out of doors on an infinite grass field, can be calculated from:

$$\overline{S}_t = \sum_i \overline{S}_i \left(\frac{t_i}{168}\right)$$

where t_i is the number of hours in a week during which an individual is located at the place having the shielding factor $\overline{S}_i$ (which can either be a weighted shielding factor or a single shielding factor). Four different locations are considered with shielding factors and time distribution within one week as shown in table 6.2.

Table 6.2. Shielding factors for different types of location

Location	Percentage of time	Semi-urban area	Urban area
Out of doors	6.2	0.5	0.05
Transport	5.0	0.5 × 0.5	0.5 × 0.05
Work/school	23.8	0.0015	0.0015
Home	65.0	S_{house}	S_{town}

Both for semi-urban and urban areas, the shielding factors (Al 78) include a factor 0.5 owing to the outdoor shielding effect of the surrounding buildings, etc. For transport, a further reduction of 0.5 is included to account for the shielding effect of the vehicle itself. An investigation (La 81) carried out after the completion of the present work shows that this factor can be justified. As mentioned previously, there is moreover a reduction of the shielding factors by a factor 10 in urban areas to compensate for the lesser deposition on walls, roofs, asphalt, etc.

For the shielding factor of places of work, the same value was selected as for apartments on the second and third floors of four-storey buildings (0.015), based on the consideration that factories, public offices, hospitals, colleges, schools, etc., are normally larger buildings with thick walls. Further it is assumed that the deposition on these buildings and their surroundings is a factor 10 less than on grass-covered surfaces, whether these buildings are in semi-urban or in urban areas.

It is, moreover, assumed that the population of a certain municipality is employed in this municipality, too. Of course, this is a simplification but the error is counterbalanced in the summing of the collective dose for all municipalities. Further the estimated transport time is relatively large even in the case of considerable distances between homes and places of work.

Table 6.3 shows the time-averaged shielding factors for municipalities in the metropolitan area calculated using the above assumptions (He 80). The table gives the "total" shielding factors for normal residence, transport and work in the area, as well as the shielding factors for work and transport in the municipality, but assuming that non-working hours are spent outside the contaminated area.

For the sake of completeness, it should be noted that both the weighted and the time-averaged shielding factors are calculated by averaging over the distribution of homes. For this reason they can only be used to calculate the collective doses and the average individual doses for the evaluation of stochastic health effects, but not for calculating individual doses for the assessment of non-stochastic health effects.

Table 6.3. Time-averaged shielding factors in % for different municipalities:

Municipality	Total	Work
Copenhagen*	0.75	0.16
Frederiksberg*	0.74	0.16
Ballerup	6.84	1.29
Brøndby*	0.93	0.16
Gentofte	6.78	1.29
Gladsaxe	6.71	1.29
Glostrup*	1.11	0.16
Herlev	7.40	1.29
Albertslund	7.57	1.29
Hvidovre	6.75	1.29
Høje Tåstrup	7.42	1.29
Ledøje-Smørum	9.32	1.29
Rødovre	6.94	1.29
Ishøj	6.73	1.29
Tårnby	7.19	1.29
Vallensbæk	7.74	1.29
Greve	8.58	1.29
Gundsø	9.31	1.29
Køge	7.72	1.29
Ramsø	9.32	1.29
Roskilde*	1.21	0.16
Solrød	8.49	1.29

* see the footnote to table 6.1.

6.2. Ploughing

When evaluating the long-term consequences of land contamination it is necessary to take into account the fact that agricultural areas - no matter whether it is decided to destroy the crops growing on them during the first year after the accident or not - will be ploughed up sooner or later. Hence the contamination, if not removed by scraping or other procedures, will be ploughed down under a shielding layer of soil. The time that elapses from contamination to ploughing depends, naturally enough, on the season of the year and on which measures are perhaps taken. Modern agricultural implements imply, however, that the actual time spent by workers on the fields is limited, and if steps are taken to rapidly plough or dig over the areas surrounding the farmhouse and yard, then the time of routine ploughing will only be of significance for doses received by road-users in agricultural areas.

Ro 82 gives further details of the experiments that were carried out at Risø for studying the effect of ploughing, while He 79 describes calculations of shielding factors for ploughing. The experiments - combined with the calculations - showed that ploughing reduces the radiation levels on fields by a factor 15-18. Later ploughing must be expected to reduce this effect, and in He 79 there are calculations showing that a homogeneous mixing of the activity in the uppermost 25 cm of the soil results in a reduction factor of 6.

The assumption of homogeneous mixing is, however, cautious - if the first ploughing is deeper than the subsequent ones, then the majority of the deposited activity will be retained in the deep layer.

The effect of ploughing was not taken into account in the dose calculations.

6.3. The effect of run-off and of weathering

The deposited activity will vanish more rapidly than is determined by the physical half-life as a result of the weather and especially of rain. The run-off effect follows upon precipitation during or in the first couple of days after deposition, while weathering is a long-term effect.

Wa 82 reports on a number of experiments carried out at Risø for studying these effects.

A run-off of 10% was measured in one experiment during precipitation. In others there was an effect of the same magnitude from the first heavy rain after contamination, if this rain occurred reasonably rapidly (within a couple of weeks) after contamination.

These results are in agreement with information given in Ri 76. Admittedly, a larger immediate run-off effect is stated to occur here, but this is associated with considerably heavier rain than is normally experienced in Denmark. In Ri 76 it is stated that a run-off effect is first manifested after more than 3 mm of rain have fallen on dry roads: however, if the asphalt already has a wet surface because of rain that fell earlier, then an initial run-off can be expected after 1.5 mm of rain.

In a different experiment a run-off of approximately 30% was measured on ice-covered roads while snow was falling and temperatures were above freezing. As this value includes clearing of the road by sweeping, etc., it should be possible to use it to ascertain that the effect is at any rate no less in snow than in rain.

In the weathering experiments the deposited activity was studied throughout a period lasting from one to two months. Within this time it was possible to ascertain that activity disappears from asphalt surfaces more rapidly than can be accounted for by the physical half-life.

By taking a simple average, weathering was found to give a half-life of 27 days in the initial period; hereafter activity vanishes with a half-life that is very close to the physical half-life.

In Ga 63, Gale reports a measured weathering half-life for agricultural land of approximately one year. It seems reasonable that activity vanishes more rapidly from an asphalt surface than the time it takes to penetrate into the soil.

Using a 27-day half-life for weathering and otherwise Gale's half-life of approximately 100 years for the long-term effect, then the disappearance of Cs activity from asphalt surfaces can be described by the reduction factor (Wa 82):

$$V(t) = 0.6 \cdot \exp(-9.5\ t) + 0.4\ \exp(-0.0075\ t)$$

where t is given in years. This reduction factor is used both for asphalt roads and for the surfaces of structures in the dose calculations presented in this report.

6.4. References

Al 78 Aldrich, D.C. et al., 1978, "Public protection strategies for potential nuclear reactor accidents: Sheltering concepts with existing public and private structures", SAND77-1725.

Au 59 Auxier, J.A. et al., 1959, "Experimental evaluation of the radiation protection afforded by residential structures against distributed sources", CEX-58.1, USAEC.

Bu 66 Burson, Z.G., 1966, "Experimental radiation measurements in conventional structures. Part I: Radiation measurements in two two-storey and three one-storey typical residential structures before and after modification", CEX-59.7B, USAEC.

Bu 70 Burson, Z.G., 1970, "Experimental evaluation of the fall-out radiation protection provided by structures in the control point area of the Nevada Test Site", CEX-69.5, USAEC.

Da 77 Danmarks Statistik, 1977, "Boligopgørelse 1. april 1977. Tabeller for udvalgte kommuner i hovedstadsregionen". (Housing report 1 April 1977. Tables for selected municipalities in the metropolitan area).

Ga 63 Gale, H.J. et al., 1963, "The weathering of caesium 137 in soil", AERE-R-4241.

He 79 Hedemann Jensen, P., 1979, "Dæmpningsfaktorer for gammastråling fra deponeret radioaktivitet opnået ved pløjning af jord og asfaltpålægning af veje", Risø-arbejdsrapport. (Attenuation factors for gamma radiation from deposited activity achieved by ploughing the soil and asphalting the roads) Risø work report.

He 80 Hedemann Jensen, P., 1980, "Gennemsnitlige skærmfaktorer for gammastråling fra deponeret aktivitet på bygninger og veje i hovedstadsregionen", Risø-arbejdsrapport. (Average shielding factors for gamma radiation from deposited activity on structures and roads in the metropolitan region) Risø work report.

He 82 Hedemann Jensen, P., 1982, "Shielding factors for gamma radiation from activity deposited on structures and ground surfaces", Risø-M-2270 (In preparation).

La 81 Lauridsen, B. and Hedemann Jensen, P., 1981, "Shielding factors for vehicles to gamma radiation from activity deposited on ground surfaces", paper presented at "Joint radiation protection meeting on radiological impact of nuclear power plants and other nuclear installations on man and his environment", Lausanne, Switzerland, 30.9 - 2.10.1981.

Ri 76 Ritchie, L.T. et al., 1976, "Effects of rainstorms and runoff on consequences of nuclear reactor accidents", SAND76-0429.

Ro 82 Roed, J., 1982, "Reduktion af dosis ved nedpløjning af gamma-aktive isotoper" (Dose reduction by ploughing down gamma-active isotopes), Risø-M-2275 (in preparation).

Wa 82 Warming, L., 1982, "Weathering and decontamination of radioactivity deposited on asphalt surfaces", Risø-M-2273 (in preparation).

7. DOSES AND CONTAMINATION IF NO COUNTERMEASURES ARE IMPLEMENTED

7.1. Introduction

This chapter presents an evaluation of the maximum contamination levels, and the doses originating from these, that could be expected on Danish territory should there occur a release of radioactivity at Barsebäck, and provided that no special measures are taken except to warn the population to stay indoors with windows and doors closed during the passage of the cloud.

Calculations were made for situations comprising a core meltdown, containment failure, and wind direction towards Copenhagen. Applying these assumptions, the consequences were evaluated partly under the most probable circumstances (BWR-3 release, Pasquill stability category D without rain and a wind speed of 10 m/s) - in the following called "the BWR-3 case" - and partly under extremely unfortunate and extremely improbable circumstances (BWR-2 release, Pasquill stability category F with meandering and without rain and with a wind speed of 5 m/s) - in the following called "the BWR-2 case".

Doses and contamination levels were calculated by means of Risø's consequence calculation model, PLUCON 2, which is based on the Gaussian dispersion model. This is discussed in greater detail in chapter 5, which also deals with the meteorological assumptions for the calculations. A detailed description of the model is given in Th 80.

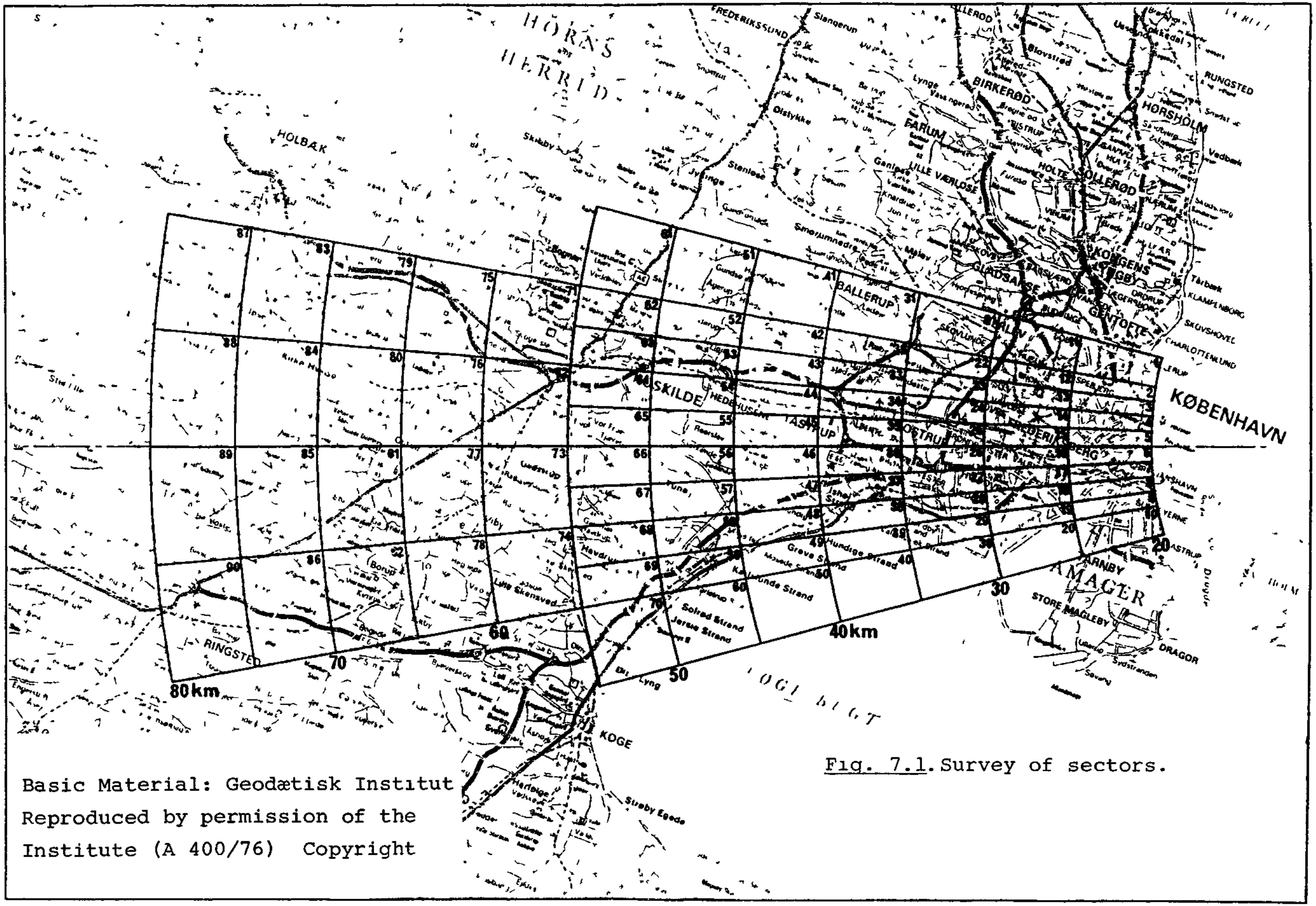
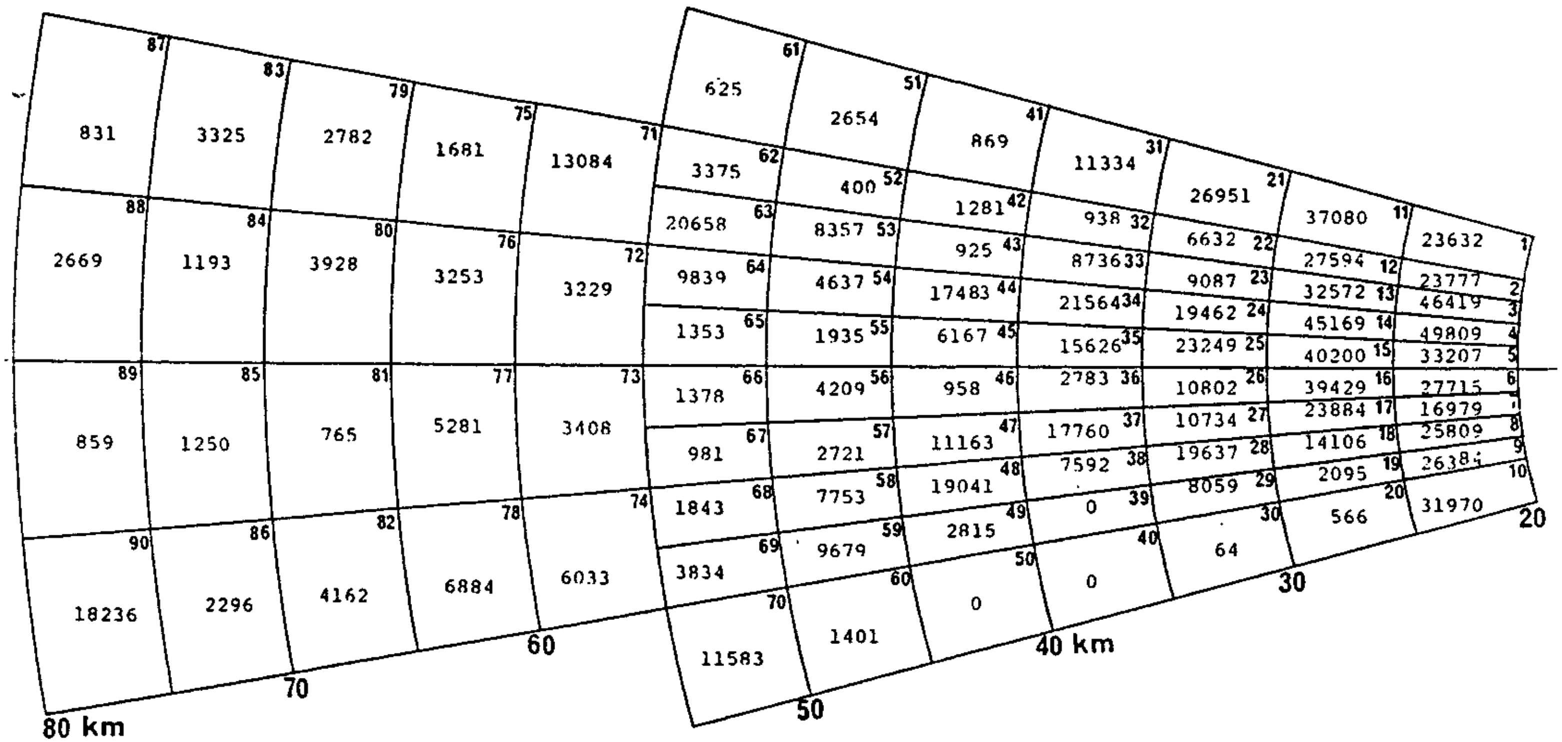


Fig. 7.1. Survey of sectors.



<u>Fig. 7.2.</u> Population density
permanent residents
forecast for 1992

7.2. General calculation assumptions

The assumptions for the calculations are described in greater detail in chapters 3, 4, 5 and 6. A summary of some of the most important of these is given here.

7.2.1. Geography

It was decided to consider only the wind direction that is most unfavourable with respect to the collective doses, i.e., that in the direction toward 249° (WSW, north = 360°).

The area for which detailed calculations were made of external gamma doses from deposited radioactivity is, as shown in fig. 7.1, the distance interval 20-55 km from Barsebäck and the angle interval 234° to 264°, as well as the distance interval 55 to 80 km from Barsebäck and the angle interval 239° to 259°.

As shown on the figure, this area is divided up into 90 sectors, the central part of the area being divided into smaller sectors than the outer. The population density is given in fig. 7.2.

7.2.2. Deposition velocity

As discussed at greater length in chapter 4, it is assumed cautiously that the deposition velocity is 0.2 $cm \cdot s^{-1}$ for all smooth surfaces (roofs, walls and roads) but 2 $cm \cdot s^{-1}$ for fields, gardens, etc.

Because of calculation technicalities the deposition velocity was put at 2 $cm \cdot s^{-1}$ overall, but the lesser velocity in urban areas is accounted for by multiplying by a factor 0.1 the shielding factors for the municipalities concerned. The acceptability of this step is discussed in more detail in chapter 6.

7.2.3. Weathering and ploughing

A correction was made for the weathering of surface deposition using a factor

$$0.6 \cdot e^{-9.5 \cdot t} + 0.4 \cdot e^{-0.0075 \cdot t} \text{ (t in years)}$$

in the area ranging from 20 to 80 km from Barsebäck. This factor is based on the experiments described in section 6.

Ploughing is not taken into account.

7.2.4. Shielding factors for normal residence and work

Here the shielding factor is defined as the ratio between the dose rate at a given point and the dose rate 1 meter above a grass field of infinite extent.

The weighted shielding factors for homes are calculated using the Bureau of Statistics' distribution of these in 22 municipalities (see chapter 6). Time-averaged shielding factors are calculated using the following distribution of the time spent in various activities:

time spent:	out of doors	6.2%
:	in transport	5.0%
:	at work	23.8%
:	inside the home	65.0%

As mentioned in 7.2.2, a factor 0.1 is introduced into the calculation of shielding factors for municipalities of urban character to take into account the lesser deposition velocity.

Based on an estimate of the distribution of the area of the 22 municipalities over the 70 sectors, the time-averaged shielding factors for these sectors are calculated by means of a simple area weighting of municipality shielding factors (see table 6.3).

For distances of more than 55 km, a constant shielding factor of 0.077 for "normal" residence and of 0.013 for work including transport are included in the calculations.

Table 7.1 shows for each sector the "total" time-averaged shielding factors for normal residence, transport and work in the sector concerned, as well as the time-averaged shielding factors for work and transport in the sector concerned (but assuming that non-working hours are spent outside the contaminated area).

Table 7.1. Time-averaged shielding factors (%)

Sector	"Total"	Work and transport	Sector	"Total"	Work and transport
1	3.46	0.67	36	6.26	1.10
2	0.75	0.16	37	6.16	1.10
3	0.75	0.16	38	6.82	1.20
4	0.75	0.16	39	-	-
5	0.74	0.16	40	-	-
6	0.71	0.16	41	8.84	1.30
7	0.75	0.16	42	7.42	1.30
8	0.75	0.16	43	7.42	1.30
9	0.75	0.16	44	7.42	1.30
10	2.68	0.50	45	7.04	1.30
11	4.40	0.84	46	7.47	1.30
12	1.68	0.33	47	8.40	1.30
13	1.80	0.35	48	8.58	1.30
14	1.66	0.33	49	8.58	1.30
15	1.95	0.39	50	-	-
16	1.82	0.36	51	9.31	1.30
17	1.95	0.39	52	6.96	1.10
18	2.55	0.50	53	6.18	1.10
19	1.95	0.39	54	2.14	0.33
20	0.75	0.16	55	7.10	1.20
21	6.69	1.20	56	6.74	1.00
22	4.15	0.72	57	8.58	1.30
23	4.47	0.78	58	8.56	1.30
24	2.98	0.52	59	8.53	1.30
25	1.84	0.33	60	8.49	1.30
26	2.39	0.44	61	5.66	0.78
27	4.42	0.84	62	1.21	0.16
28	5.30	1.00	63	1.21	0.16
29	6.75	1.30	64	1.21	0.16
30	6.75	1.30	65	1.57	0.22
31	8.31	1.30	66	7.03	1.00
32	7.53	1.30	67	9.23	1.30
33	7.53	1.30	68	8.62	1.30
34	6.88	1.20	69	8.49	1.30
35	6.23	1.10	70	7.99	1.30
			71-90	7.70	1.30

The shielding factors shown in table 7.1 are used for calculation of the individual and population doses for, respectively, "normal" residence and work/transport alone. "Normal" residence is here understood as a lifestyle without alteration in the usual pattern of time spent out of doors/indoors, in transport and at work (the reference situation).

7.3. The "most probable" accident circumstances

WASH-1400 (NRC 77) gives the following probabilities for the three types of release that comprise both a core melt-down and containment failure:

BWR-1	1×10^{-6}	per reactor year
BWR-2	6×10^{-6}	per reactor year
BWR-3	2×10^{-5}	per reactor year

As stated in chapter 3, recent investigations have shown, however, that the BWR-1 release is of much less probability than that given in WASH-1400.

The BWR-3 release is the most probable of these hypothetical releases (which, in fact, have never occurred).

As discussed in chapter 5, the most probable meteorological conditions in Denmark comprise a Pasquill category D situation without precipitation and with a wind speed of 10 $m \cdot s^{-1}$.

The first type of accident (the "BWR-3 case") can therefore be defined as follows:

Type of release	BWR-3
Duration of release	3 hours
Thermal release	5.9 MW
Release height	0 m
Stability	Pasquill D, without precipitation
Wind speed	10 $m \cdot s^{-1}$

7.4. "Worst" accident circumstances

As discussed at greater length in chapter 3, a BWR-2 release is considered the type of release that, in the case of a boiling-water reactor, could give rise to the worst contamination consequences.

In chapter 5 there are descriptions of the weather situations that could be unfavourable for Danish territory in the event of a large-scale accident at the Barsebäck plant.

These are situations where there is relatively large dry deposition (v_g = 2 cm/s on rough surfaces), such as it appears from the following table:

Situation no.	Name	Atmospheric stability (Pasquill)	Wind speed [m/s]	Wet deposition parameter [s^{-1}]	Dry deposition parameter [cm/s] on rough surfaces
1	B, dry	B	10	0	2
2	D, dry	D	10	0	2
3	D, rain [75% run-off]	D	10	$5 \cdot 10^{-5}$	2
4	F, dry	F	5	0	2
5	F, meander [factor 4]	F	5	0	2

To determine which of these situations is/are the most unfavourable for Danish territory, comparative calculations of the following factors were made:

a. Area inside the isodose curves
b. Number of people subject to given dose
c. Collective doses in given individual dose intervals
d. Area inside isoconcentration curves for caesium-137.

When evaluating the various situations, consideration is given to individual and collective doses from external gamma radiation originating from deposited radioactivity integrated over 30 years from the start of the accident. It must be noted that the choice of integration period and shielding factors for buildings and the like is of no importance for the relative assessment of the different combinations of parameters. The relative variation of the dose rate with time (i.e., dose rate at the time t in relation to the dose rate 24 hours after the start of the accident) depends only on the isotopic composition of the releases.

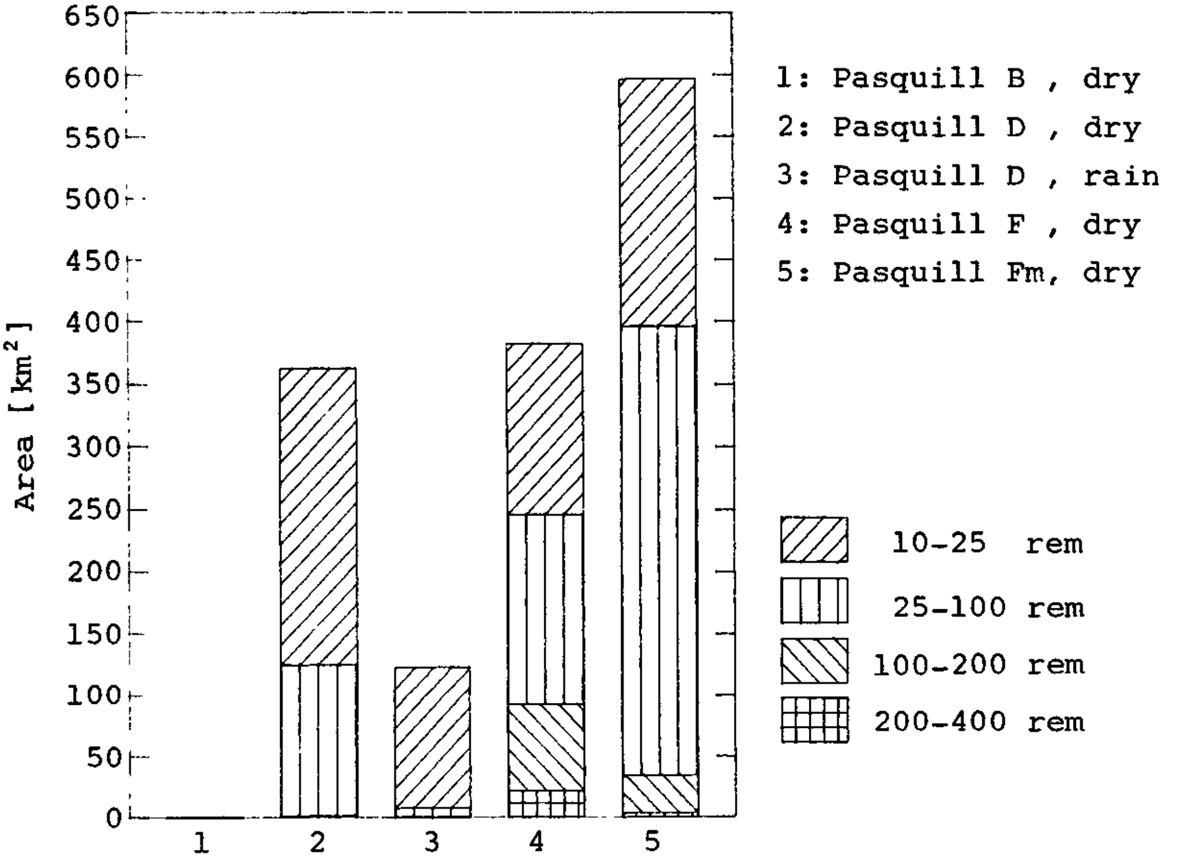
The results of this parameter study are shown on figs. 7.3-7.6. Regardless of which of the above criteria is applied, the figures show that situation no. 5 represents the most unfavourable circumstances.

The second type of accident (the BWR-2 case) can therefore be defined as follows:

Type of release	BWR-2
Duration of release	3 hours
Thermal release	9 MW
Height of release	0 m
Stability	Pasquill F
Meandering factor	4
Wind speed	5 $m \cdot s^{-1}$

To investigate whether under these accident circumstances non-stochastic health effects would occur in connection with the passage of the cloud, calculations were made of external gamma doses from the cloud, inhalation doses to the bone marrow (integrated over 30 days after inhalation) and effective dose equivalent from inhalation (integrated over 50 years after inhalation).

A location indoors is assumed throughout the passage of the cloud. A shielding factor of 0.6 was used for the external gamma doses from the cloud (NRC 75). The inhalation doses are reduced by a factor 0.2 to take into account the filter effect of buildings.



<u>Fig. 7.3.</u> BWR-2 parameter study:
Area (km^2) inside isodose curves.

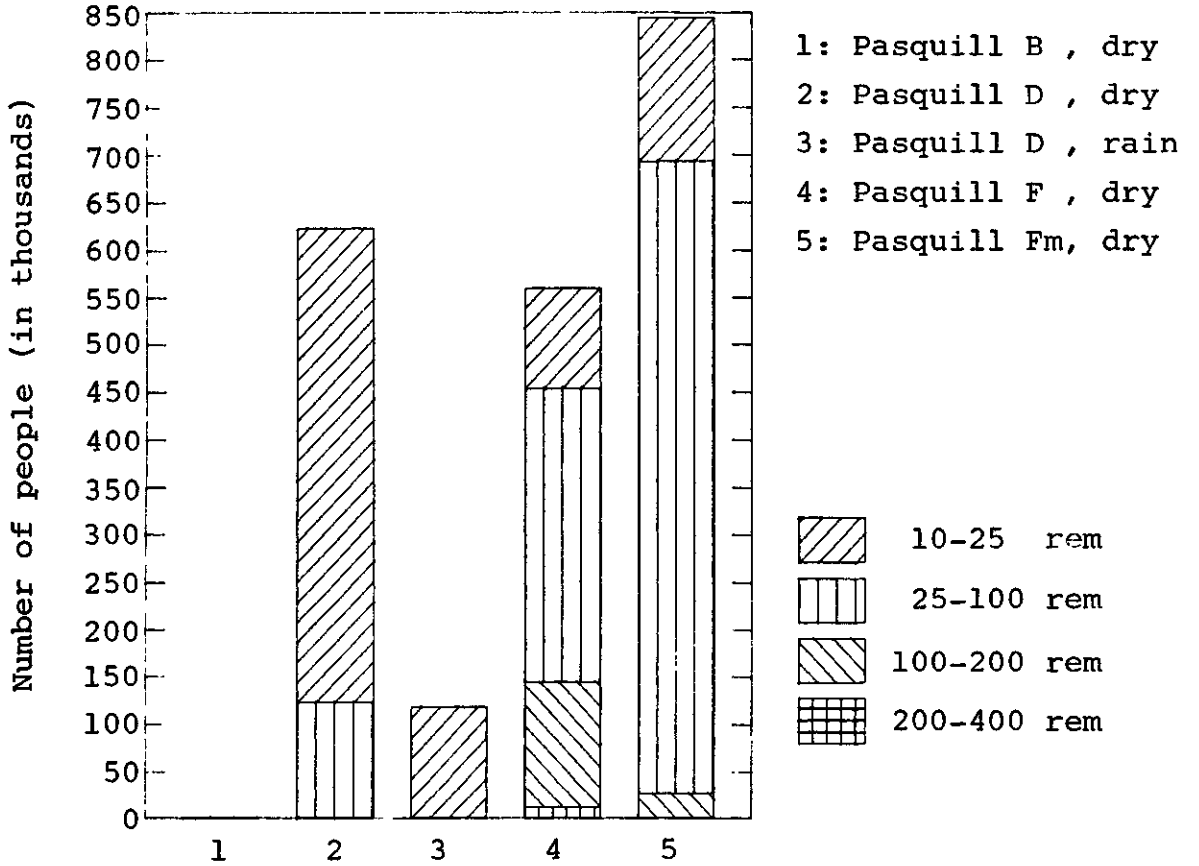
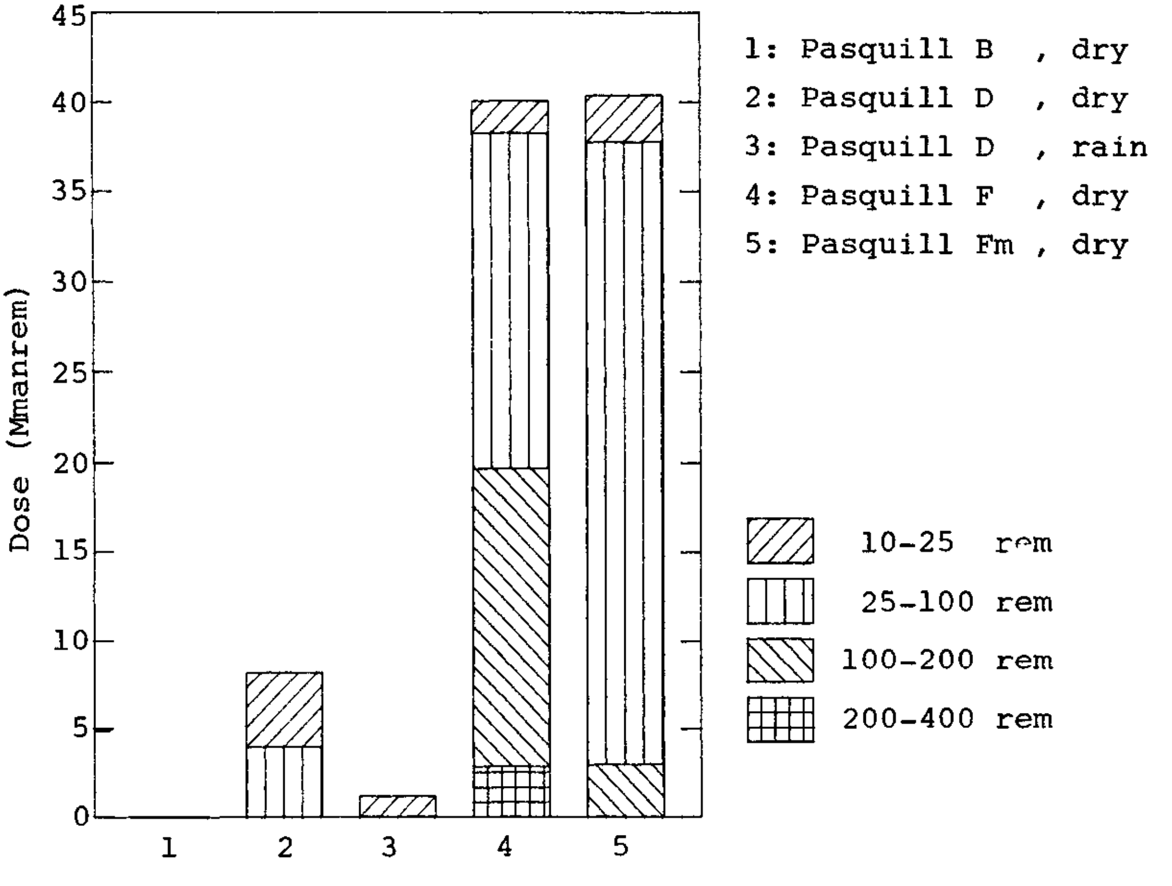


Fig. 7.4. BWR-2 parameter study: Number of people (in thousands) who would receive given doses.



<u>Fig. 7.5.</u> BWR-2 parameter study: Collective doses (Mmanrem) as function of individual doses.

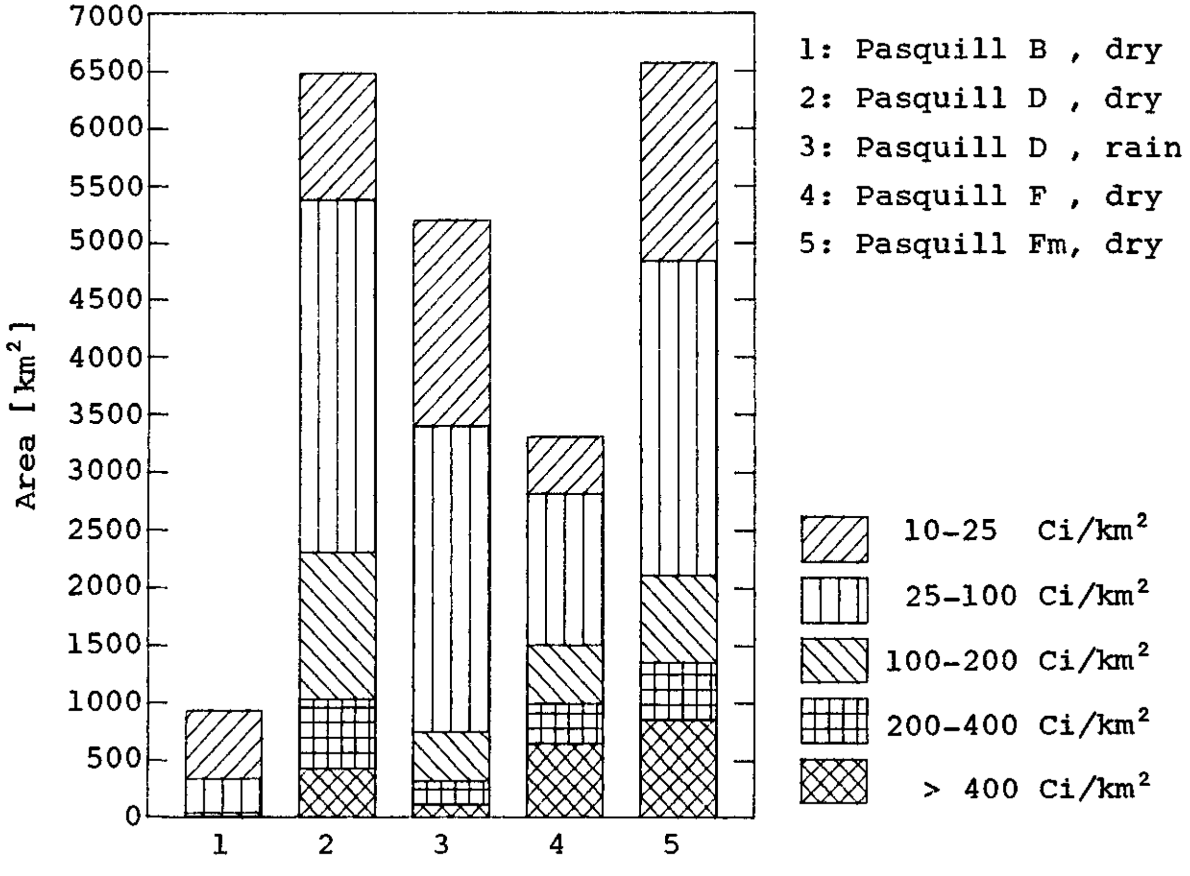


Fig. 7.6. BWR-2 parameter study: ^{137}Cs contamination area (km^2) inside isodose curves.

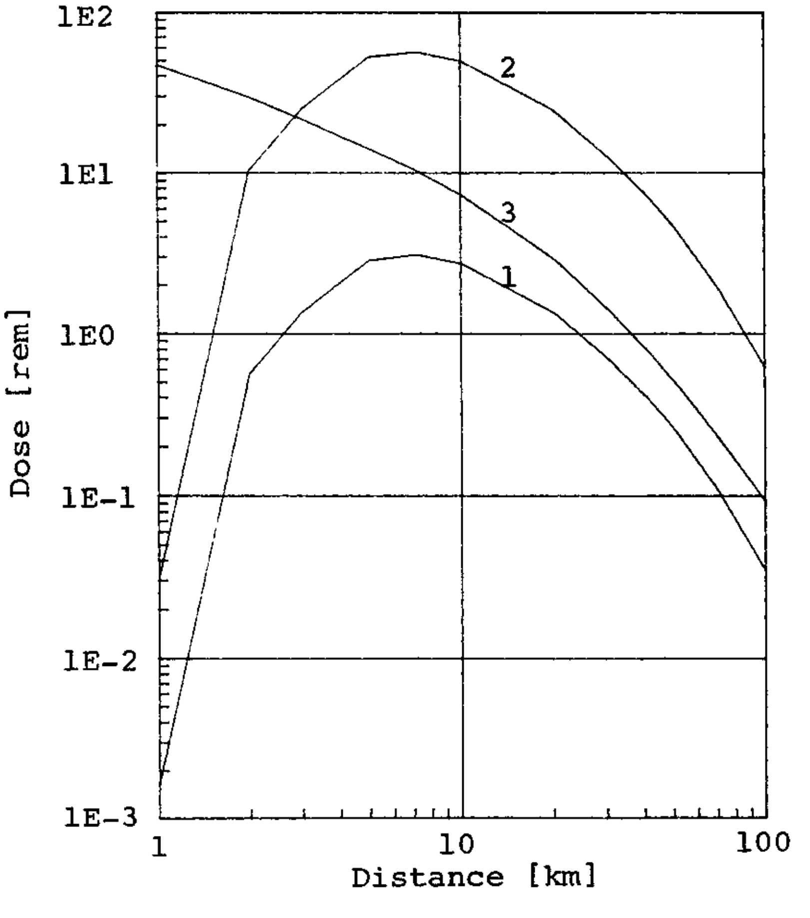


Fig. 7.7.BWR-2 case: Individual dose (rem) from the passage of the cloud.

1. Inhalation dose to bone marrow.
2. Effective dose equivalent from inhalation (integrated over 50 years).
3. External gamma dose from the cloud.

The results are shown in fig. 7.7. The maximum individual dose to bone marrow at distances more than 20 km from Barsebäck is seen to be 30 rem, which is far below the doses that give rise to non-stochastic health effects.

7.5. Doses under the "most probable" accident circumstances

Applying the assumptions mentioned in 7.2 and 7.3, the following individual doses are calculated from deposited activity in the BWR-3 case, assuming people pursuing normal activities.

Fig. 7.8. Individual doses in the first month
Fig. 7.9. Individual doses in the second month
Fig. 7.10. Individual doses in 30 years.

The isodose curves for people pursuing normal activities (individual doses integrated over 30 years) are found to have the following approximate dimensions:

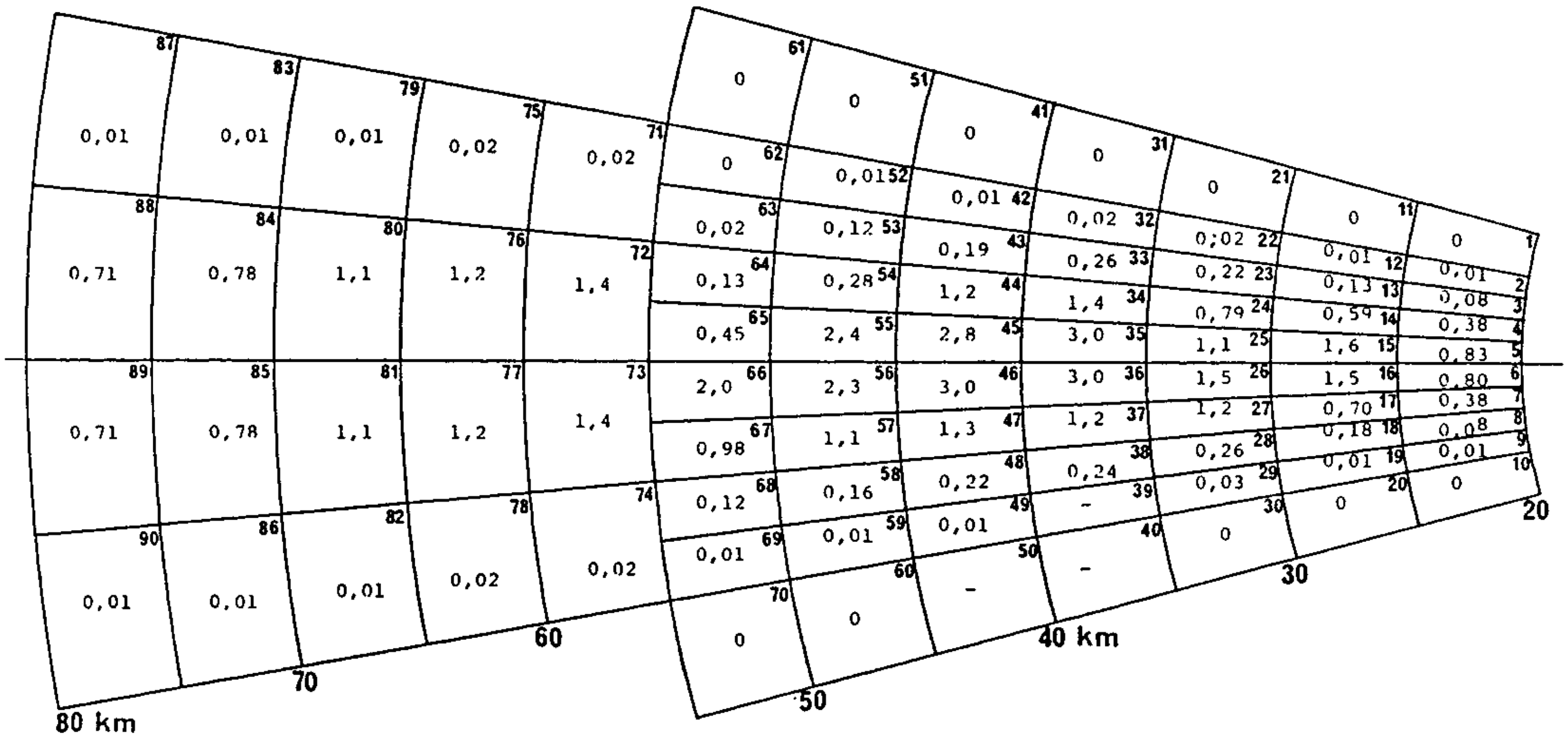
Dose	Area [km^2]
5 rem	326
10 rem	67

The collective doses over 30 years for the area ranging up to 110 km from Barsebäck are calculated to 3.6 Megamanrem.

7.6. Doses under the "worst" accident circumstances

Applying the assumptions given in 7.2 and 7.4, the following individual doses were calculated for the BWR-2 case:

Fig. 7.11. Individual doses in the first month
Fig. 7.12. Individual doses in the second month
Fig. 7.13. Individual doses in the third month
Fig. 7.14. Individual doses in 30 years.



<u>Fig. 7.8</u>. BWR-3 case: Individual doses (rem) in the <u>first month</u>.
Normal life style.

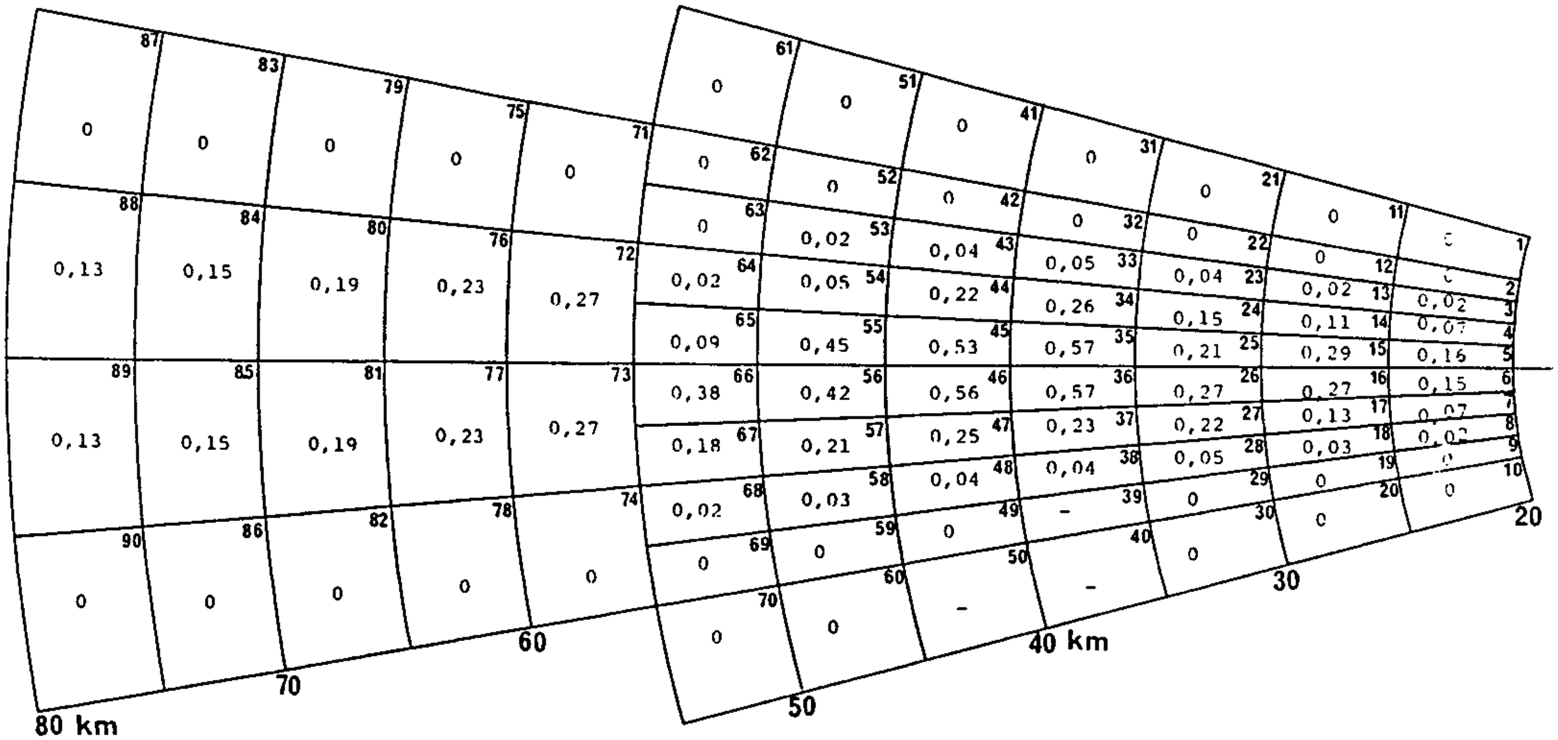


Fig. 7.9. BWR-3 case: Individual doses (rem) in the second month.
Normal life style.

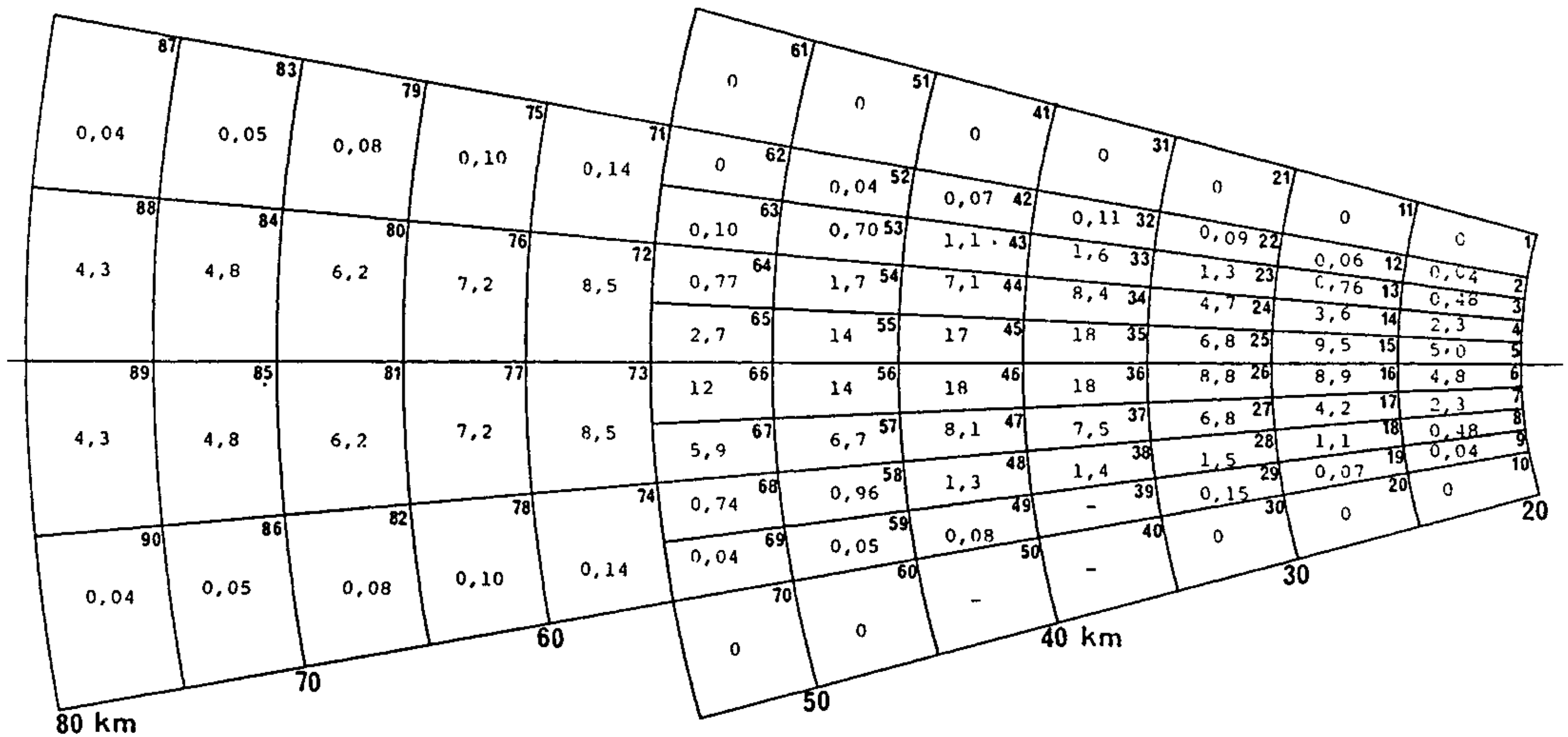


Fig. 7.10. BWR-2 case: Individual doses (rem) in 30 years.
Normal life style.

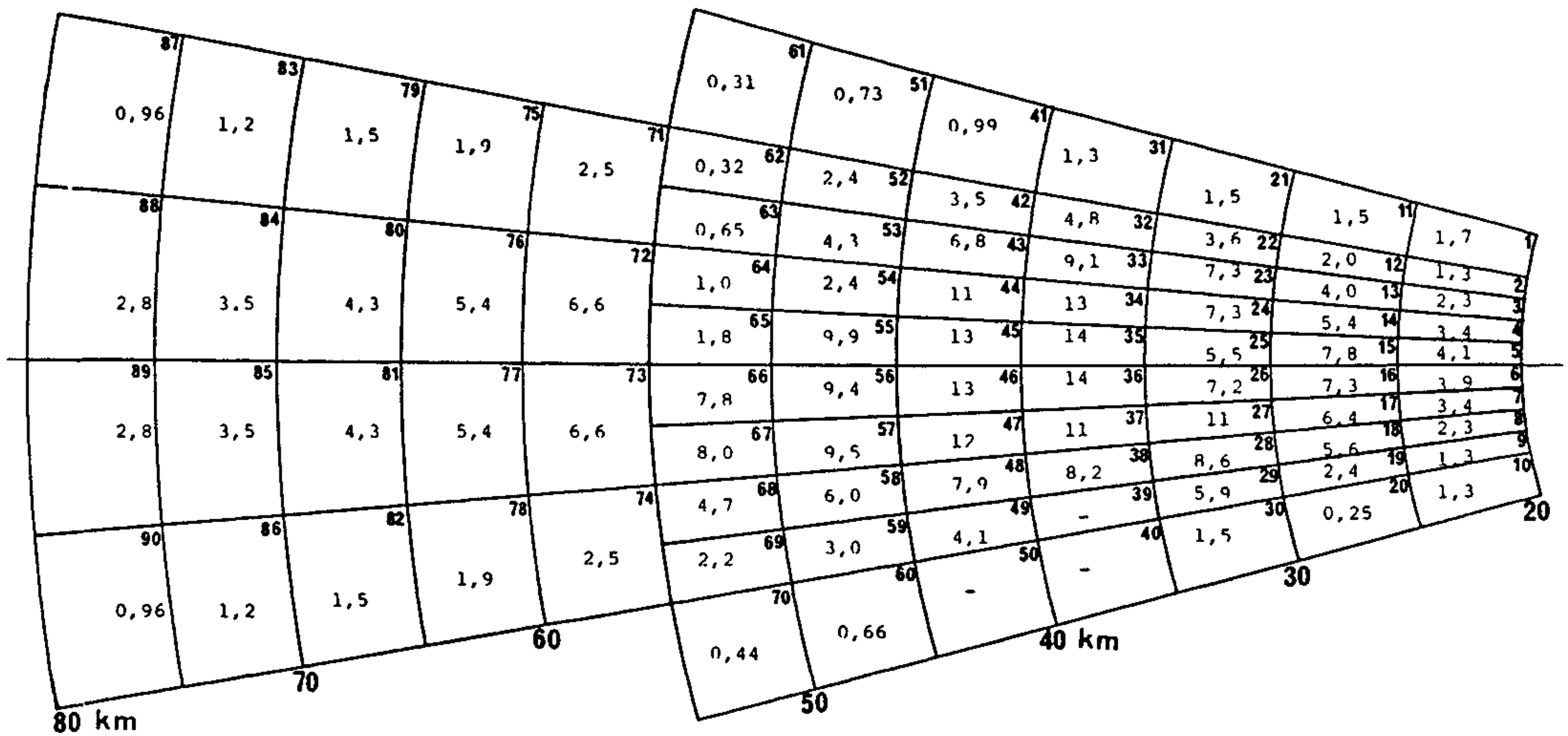


Fig. 7.11. BWR-2 case: Individual doses (rem) in the first month.
Normal life style.

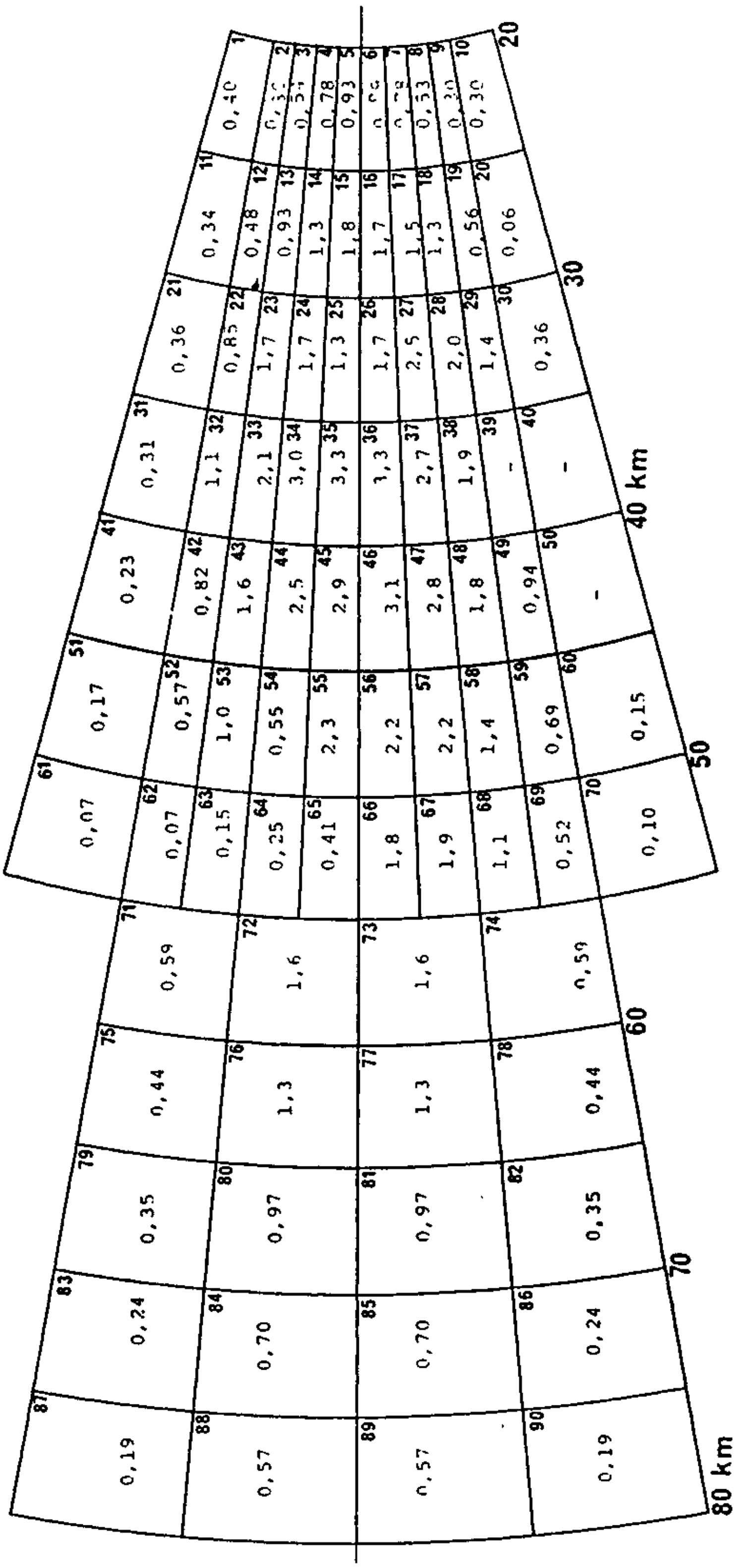


Fig. 7.12. BWR-2 case: Individual doses (rem) in the second month. Normal life style.

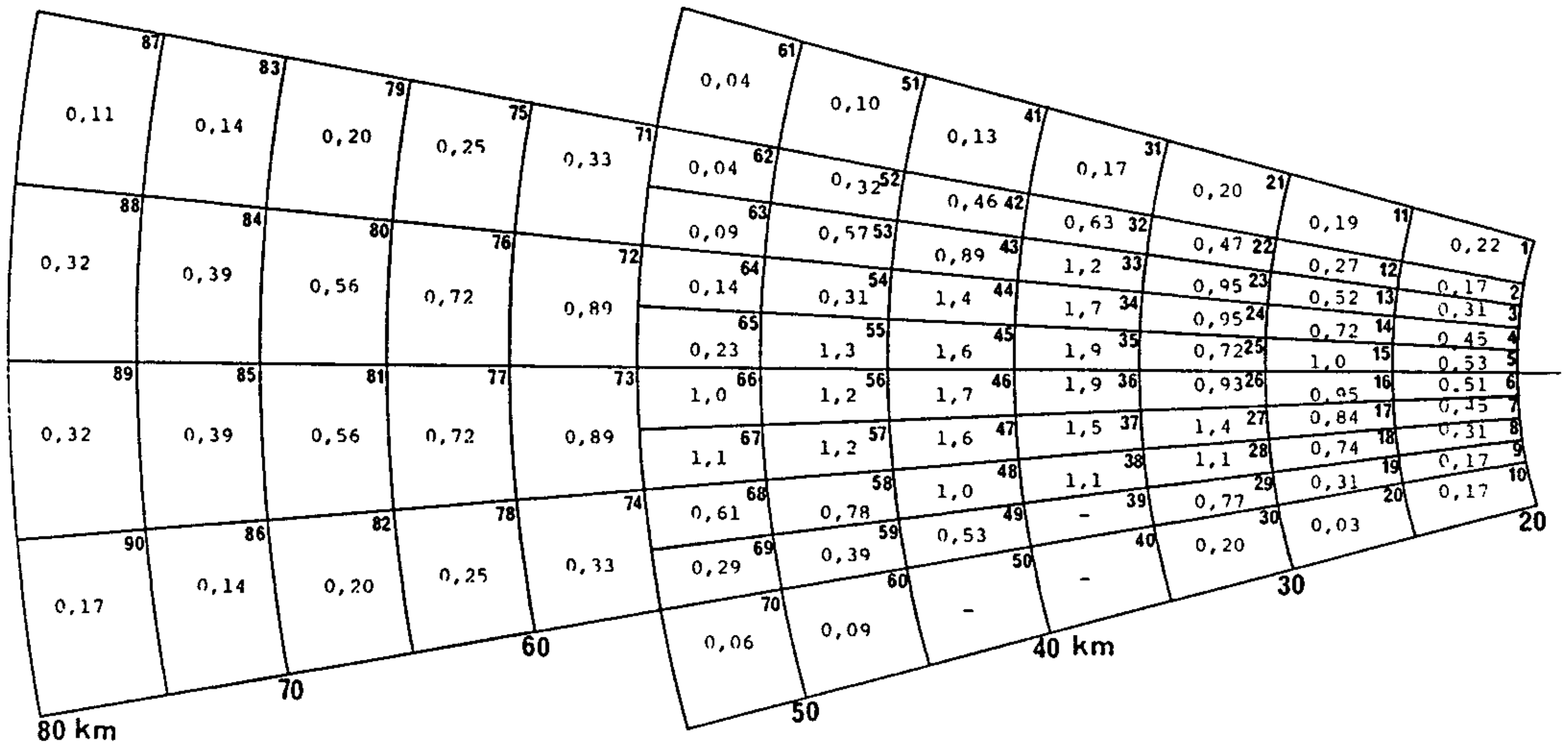


Fig. 7.13. BWR-2 case: Individual doses (rem) in the third month.
Normal life style.

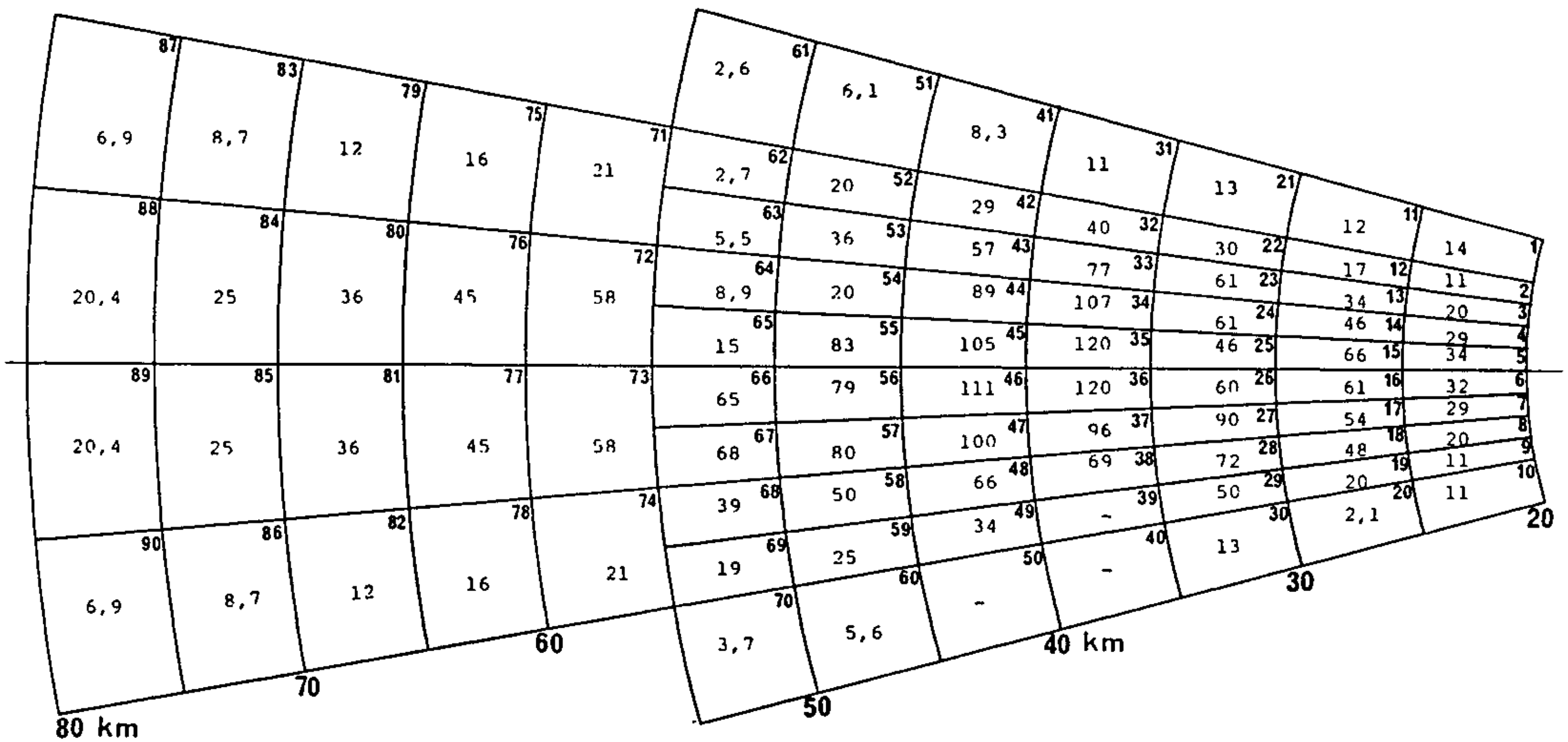


Fig. 7.14. BWR-2 case: Individual doses (rem) in 30 years.
Normal life style.

Isodose curves applying to those pursuing normal activities (individual doses integrated over 30 years) are found to be of the following approximate dimensions:

Dose	Area [km^2]
5 rem	2000
30 rem	475
100 rem	55

The collective doses over thirty years for the area up to 110 km from Barsebäck are calculated to 41 Megamanrem.

7.7. References

NRC 75 NRC, 1975, "Reactor Safety Study. An assessment of accident risks in U.S. commercial nuclear power plants", WASH-1400 (NUREG 75/014).

TH 80 Thykier-Nielsen, S., 1980, "The Risø model for calculating the consequences of the release of radioactive material to the atmosphere", Risø-M-2214.

8. DOSE-REDUCING MEASURES RELATING TO SURFACE CONTAMINATION

8.1. Introduction

This chapter is an assessment of the decontamination measures that could be appropriate in the two types of accident described in chapter 7.

Different decontamination methods are discussed and their efficiency described, partly on the basis of experimental and theoretical studies carried out at Risø during the last couple of years. The influence on dose levels - particularly the doses in the BWR-2 case - is evaluated through calculating doses associated with single measures and with a combination of these.

The measures to be implemented after a given accident must firstly be justifiable - i.e., the costs associated with the decontamination measures, hereunder radiation doses to decontamination workers, must be less than the value of the dose reduction achieved through the implementation of such measures. Secondly, such a measure should only continue until the costs of the most recent part-measure (e.g., the last of a series of fire-hosing procedures) exceeds the value of the associated dose reduction.

The principles given above naturally presuppose that only stochastic health effects are possible in the area in question. As shown in chapter 7, this would be the case throughout all Danish territory even under the most extreme accident circumstances.

8.2. Decontamination processes and their efficiency

8.2.1. Decontamination of hard surfaces

There is much information concerning the decontamination of surfaces (Wi 65, Wi 66, Cl 63), but the great majority of the data concern decontamination associated with fallout resulting from the explosion of nuclear weapons near the area under consideration.

For surfaces, the possibilities of decontamination depend heavily on the character of the surfaces, e.g., roughness, porosity and chemical properties, as also on the size of the deposited particles. Fallout particles close to the site of a nuclear explosion are relatively large, i.e., greater than 20 μm, while the particles from a core-melt accident are assumed to be less than 4 μm in size. For this reason the results found for the decontamination of radioactive particles originating from nuclear weapon explosions cannot be used as a direct measure for the decontamination that could be obtained for particles deposited as a result of a core-melt accident.

The adhesion of radioactive contamination depends on whether the particles are deposited with rain, or whether they are deposited in dry weather. Moreover, the result of decontamination depends strongly on how rapidly such a process can be carried out. This applies in particular to dry deposition, as rain will carry the radioactive material down into pores and cracks, resulting in a stronger adhesion that makes decontamination procedures difficult.

In addition to the measurements of large fallout particles (which are not relevant in the present connection), a series of decontamination experiments have been reported in which the particle size does correspond to the size that can be expected from a core melt-down (Di 61). Plutonium having a mean diameter of approximately 0.8 μm was used for this work.

8.2.1.1. Hosing, washing and sand blasting. Risø carried out a series of decontamination experiments using high-pressure hosing after a simulated deposition of radioactivity on an asphalt road.

With respect to caesium, the experiments showed that - depending on the length of time elapsing from deposition to hosing - between 40% and 5% of the material can be removed. If hosing starts relatively rapidly after deposition, about 40% can be removed but after roughly six weeks only about 5% of the remaining activity can be dislodged by high-pressure hosing (Wa 82).

In addition, Risø carried out a number of decontamination studies relating to roofing materials and the walls of structures. Here, measurements (Ro 81) showed that caesium-137 adheres particularly strongly when some time has passed since deposition; moreover, it was possible to conclude that the portion that vanishes from the surface does so in fact quite rapidly. Therefore no significant reduction of the radiation level can be presumed after the first shower of rain following on dry deposition. This finding agrees with the results of the decontamination studies relating to roads discussed above.

8.2.1.2. Vacuum-sweeping and vacuum cleaning. If roads, pavements, etc., are contaminated by dry deposition, vacuum-sweeping can remove about two-thirds of the deposited materials (Di 61). A further high-pressure hosing would give a total decontamination factor of more than 10, i.e., more than 90% of the radioactive material would be removed (Di 61).

Should there be a light shower of rain before decontamination measures are initiated, the situation deteriorates as a large part of the radioactive material would then adhere far harder to the underlying surface. Under these circumstances vacuum-sweeping would hardly have any effect.

Vacuum cleaning of the walls of single-family houses and their roofs, too, if possible, using an ordinary household vacuum cleaner would be a practicable measure in semi-urban areas: the refuse could be buried in gardens. However, no attempts should be made to wash down the walls because this leads easily to even greater adhesion of the radioactivity. Instead, high-pressure hosing could be carried out.

Vacuum cleaning can remove between a third and two-thirds of the radioactive material. A subsequent pressure hosing should be able to give a total decontamination factor in excess of 10, i.e., more than 90% of the radioactive material could be removed (Cl 63).

8.2.1.3. The laying and removal of asphalt. The application of an extra layer of asphalt (approx. 10 cm) on road surfaces is able to reduce the dose rate from gamma radiation originating from the road by a factor of approximately 5 at street level (He 79), corresponding to an 80% reduction of the activity. If the asphalt is entirely removed, corresponding to a 100% removal of activity, then the dose rate is further reduced, but this could hardly be done in the short term.

A practicable and effective dose-reducing measure is to turn over paving stones, which then act as shielding (a reduction in dose rate of 3-5 at street level).

8.2.2. Decontamination of ground surfaces

8.2.2.1. Digging gardens in semi-urban areas. The dry deposition velocity applicable to gardens is assumed to be significantly greater than that to the surfaces of structures and the surrounding streets. In the calculations in this report the deposition velocity applicable to gardens is fixed at 2 cm/s, but 0.2 cm/s for structure surfaces and roads. This implies that the calculated dose rate for those living in semi-urban areas is dominated by radiation from the grounds surrounding houses. The most efficient dose-reducing measures that can be applied in these areas is therefore to reduce the radiation from the ground - either by removing the uppermost layer of soil or by digging the activity into the soil.

If it is assumed that the activity can be buried effectively at a depth of one spit, and that paving stones can be turned over, the dose rate from activity on the ground will be reduced by a factor of approximately 6, corresponding to an activity reduction of 83%.

If, instead, grass turf and the uppermost layer of soil uncovered by grass are removed, the dose rate from the surroundings of houses in semi-urban areas could be reduced by almost 100%. This procedure does necessitate, however, the provision of dumps for relatively large amounts of soil and turf, etc. Nevertheless, a significant dose reduction could be achieved just by placing this surface material in heaps in corners of gardens - perhaps covered by a layer of uncontaminated soil.

8.2.2.2. Ploughing of agricultural areas. The dose rate applicable to residents in agricultural areas contaminated by dry deposition, or those who travel around in such areas, is dominated by the activity deposited on field and soil surfaces.

An effective reduction of the external dose rate can therefore be achieved by ploughing this activity down under the soil surface. Risø made a number of ploughing experiments in which different areas were contaminated by radioactivity and then ploughed. Dose rate measurements made before and after ploughing combined with the results from a calculation model show that reduction factors of 15-18 can be obtained for the dose rate from activity deposited on the ground as a result of normal ploughing (He 79, Ro 82).

Deep ploughing, in which the uppermost layer of soil is turned into the bottom of the plough furrow, can reduce the dose rate from activity deposited on fields 50 to 100 times (Ro 82).

8.3. Dose reduction brought about by different clean-up measures

8.3.1. Calculation method

For the calculation of the doses presented in chapter 7, use was made of a shielding factor that accounts for the circumstance that part of the gamma radiation level from activity deposited on roads, walls and roofs is absorbed by the building materials, which thus reduces the radiation dose rate indoors in relation to the dose rate out of doors.

In chapter 6 the shielding factor S is defined as:

$$S = \frac{\sum_i \dot{D}_i}{\dot{D}(\infty)} = \frac{\dot{D}_{road}+\dot{D}_{wall}+\dot{D}_{roof}}{\dot{D}(\infty)}$$

where $\dot{D}_{road}$, $\dot{D}_{wall}$ and $\dot{D}_{roof}$ is the dose rate inside the house concerned resulting from the activity deposited on, respectively, roads (gardens), walls and roofs, and $\dot{D}(\infty)$ is the dose rate 1 metre above a grass field of infinite extent. Included in the calculations of the individual components $\dot{D}_{road}$, $\dot{D}_{wall}$, and $\dot{D}_{roof}$ is the concentration of activity per m^2 surface on, respectively, roads, walls and roofs (He 82). The effect of a given dose-reducing measure can therefore be expressed by a modified shielding factor, which is calculated using the concentration of activity that would remain on the different surfaces after the implementation of the measure.

Calling the shielding factor for the reference situation (see chapter 7) S_{ref}, and the modified shielding factor after a dose-reducing measure S_{red}, then the dose reduction obtainable for a given area as a result of the dose-reducing measure is $S_{ref}/S_{red} > 1$. The doses presented in this chapter and in chapter 9 are calculated according to this principle. The calculation procedure is as follows. The doses from activity deposited on a grass field of infinite extent are multiplied by the modified shielding factor giving the doses after the dose-reducing measure. The modified shielding factors are shown in table 8.1.

8.3.2. Relocation

As an example, the effect was investigated of relocating the population from areas where the average individual dose for a given month exceeds, respectively, 3 and 10 rem.

For the BWR-3 case, the calculations in chapter 7 show that there would be no area in Denmark where the average individual dose exceeded 3 rem in any month after the accident.

For the BWR-2 case, the two relocation criteria concerned would imply the relocation of, respectively, some 600 000 and 100 000 people for the first month following upon the accident.

The relocation of people in accordance with the 10 rem and 3 rem criteria will reduce the collective doses by approximately 1 Megamanrem and 4 Megamanrem, respectively.

In relation to the total 30-year collective dose, relocation of the population from the contaminated areas appears to have only a marginal effect. This is seen, likewise, from the following temporal distribution of the total 30-year collective dose without the application of dose-reducing measures:

Period:	Collective dose
1st month	4.7 Megamanrem
2nd -	1.1 -
3rd -	0.6 -
4th-360th month	33 -

Nevertheless, it is not reasonable to conclude on these grounds alone that relocation is an unrealistic measure - the assessment should be made on the basis of the costs involved in the relocation.

8.3.3. Hosing of roads and walls of structures

In urban areas such as Copenhagen the accumulated radiation dose would be dominated by radiation from activity deposited on the walls and roofs of structures.

Assuming that fire-hosing of the roads in the urban areas of the region concerned (see chapter 7) is initiated rapidly, so that 40% of the activity is removed, the accumulated individual dose in the decontaminated areas would be reduced by approximately 20%. The doses in the BWR-2 case would then be reduced by a total of approximately 1.3 Mmanrem.

Furthermore, if it proved possible to fire-hose walls and roofs of buildings in urban areas, so that 10% of the activity was removed, then the above dose reduction would be increased to a total of approximately 2 Mmanrem.

These dose reductions are calculated under the assumption that the hosing operation would be completed within 14 days - in the 3rd and 4th week after the accident. The reduction would be less if hosing is carried out at a later date.

8.3.4. Removal of asphalt

In urban areas a long-term measure would be to replace paving stones and asphalt surfaces on roads, open spaces, etc. Assuming this to be accomplished in urban areas over a period of four months immediately following the accident in the BWR-2 case, it would imply a dose reduction totalling approximately 3 Mmanrem.

Instead, an approximately 20% smaller dose reduction (2.4 Mmanrem) can be obtained by turning over paving stones and applying a new, 10 cm thick layer of asphalt on top of old surfaces.

8.3.5. Digging of gardens

As mentioned earlier, the dose rate in semi-urban areas would be dominated by the activity deposited on the ground. Burying this activity would thus give a substantial dose reduction.

In calculating the shielding factors for free-standing houses, it is assumed that a garden of a house is 700 m^2 in size. The time needed to dig over this area effectively would depend on the season of the year, but 14 man-days are assumed to be a realistic estimate.

If digging starts one month after the accident, this work would imply a dose of approximately 6 manrem per garden in the most highly contaminated area after the accident in the BWR-2 case. The total dose reduction in the whole area concerned would then be approximately 20 Megamanrem.

A dose reduction some 10% greater can be obtained by removing instead the turf from lawns and the uppermost layer of soil uncovered by grass.

8.4. Dose reduction through a combination of relocation, hosing of roads and digging of gardens

8.4.1. Radiation doses to the population

Based on the above considerations, this section establishes the effect of a combination of measures as follows:

- relocation of the population from areas so long as the monthly dose exceeds 10 rem

- decontamination taking place during the 3rd and 4th week following the accident in the areas where the population has been relocated

- decontamination taking place during the first two months following the accident in other areas where the doses exceed 0.25 rem in the second month after the accident

- decontamination comprising fire-hosing of roads etc., in urban areas, and digging over the gardens in semi-urban areas.

Table 8.1. Modified shielding factors in % after fire-hosing of roads in urban areas and digging over the gardens of houses in semi-urban areas

Municipality	Shielding factors relative to a location on a grass field				
	Home	Work	Transport	Out of doors	Total
Copenhagen*	0.395	0.150	1.90	3.80	0.623
Frederiksberg*	0.333	0.150	1.90	3.80	0.583
Ballerup	1.300	0.150	4.17	8.33	1.610
Brøndby*	0.638	0.150	1.90	3.80	0.781
Gentofte	1.270	0.150	4.17	8.33	1.590
Gladsaxe	1.240	0.150	4.17	8.33	1.570
Glostrup*	0.883	0.150	1.90	3.80	0.940
Herlev	1.580	0.150	4.17	8.33	1.790
Albertslund	1.680	0.150	4.17	8.33	1.850
Hvidovre	1.260	0.150	4.17	8.33	1.580
Høje Tåstrup	1.600	0.150	4.17	8.33	1.800
Ledøje-Smørum	2.540	0.150	4.17	8.33	2.410
Rødovre	1.350	0.150	4.17	8.33	1.640
Ishøj	1.260	0.150	4.17	8.33	1.580
Tårnby	1.480	0.150	4.17	8.33	1.720
Vallensbæk	1.750	0.150	4.17	8.33	1.900
Greve	2.180	0.150	4.17	8.33	2.180
Gundsø	2.530	0.150	4.17	8.33	2.410
Køge	1.740	0.150	4.17	8.33	1.890
Ramsø	2.540	0.150	4.17	8.33	2.410
Roskilde*	1.010	0.150	1.90	3.80	1.020
Solrød	2.130	0.150	4.17	8.33	2.150

*) Reckoned as urban areas, cf. note to table 6.1.

Table 8.1 shows the modified shielding factors that take into account the effect of these decontamination measures.

When calculating population doses in the non-relocated areas, which are assumed to be decontaminated over two months, use is made of the shielding factors for the reference situation (cf. chapter 7) in the first month and thereafter of the shielding factors from table 8.1. The effect of the measure is thus introduced instantaneously in the middle of the time interval - which is done because of calculation technicalities.

Figure 8.1 shows the modified shielding factors for the individual sectors undergoing the clean-up. These shielding factors are obtained by distributing the shielding factors for the municipalities by simple area weighting.

Figure 8.2 shows the sectors where individual doses during the first month exceed 10 rem in the BWR-2 case. It is proposed that the population in these sectors is relocated during the first month. The sectors cover some 80 km^2. It seems fairly realistic to envisage that roads and pavements would be fire-hosed and gardens dug over in these areas during the 3rd and 4th week following the accident. As appears from the following, this implies that in no area would the individual doses exceed 3 rem in the second month. In the whole area where doses exceed 0.25 rem in the second month, it is assumed, as earlier stated, that measures are carried out during the first two months after the accident.

Individual doses would not exceed 3 rem/month in any area in the BWR-3 case. This implies that no relocation is foreseen and that other measures are only carried out during the first two months in the area where individual doses exceed 0.25 rem in the second month.

Sectors with an original shielding factor out of doors of less than 0.20 are here defined as urban areas. Figures 8.3 and 8.4 show the areas that, applying this definition, should be hosed and dug over in the BWR-2 and BWR-3 cases, respectively. Natural-

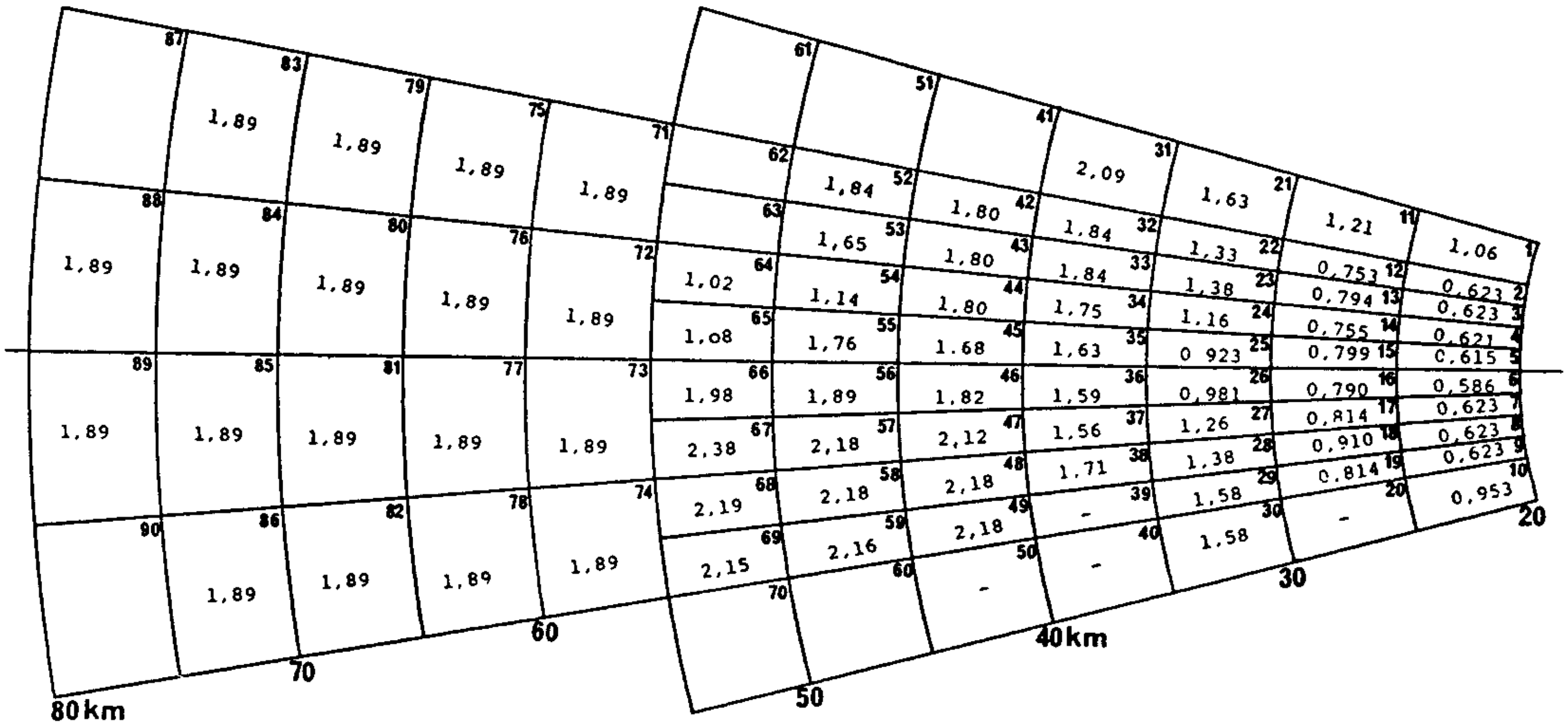


Fig. 8.1. Modified shielding factors in % after fire-hosing and digging of gardens.

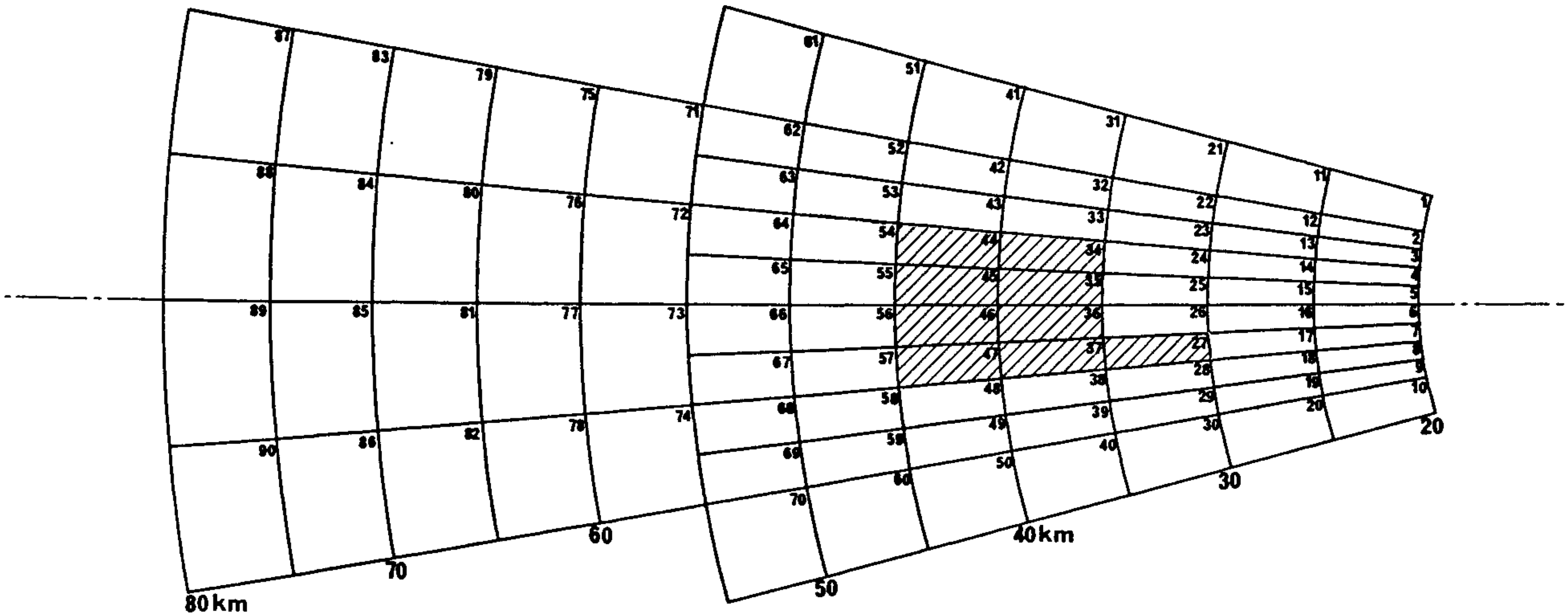


Fig. 8.2. BWR-2 case.
Sectors where the individual doses exceed 10 rem during the first month.
Number of inhabitants: 100 000.

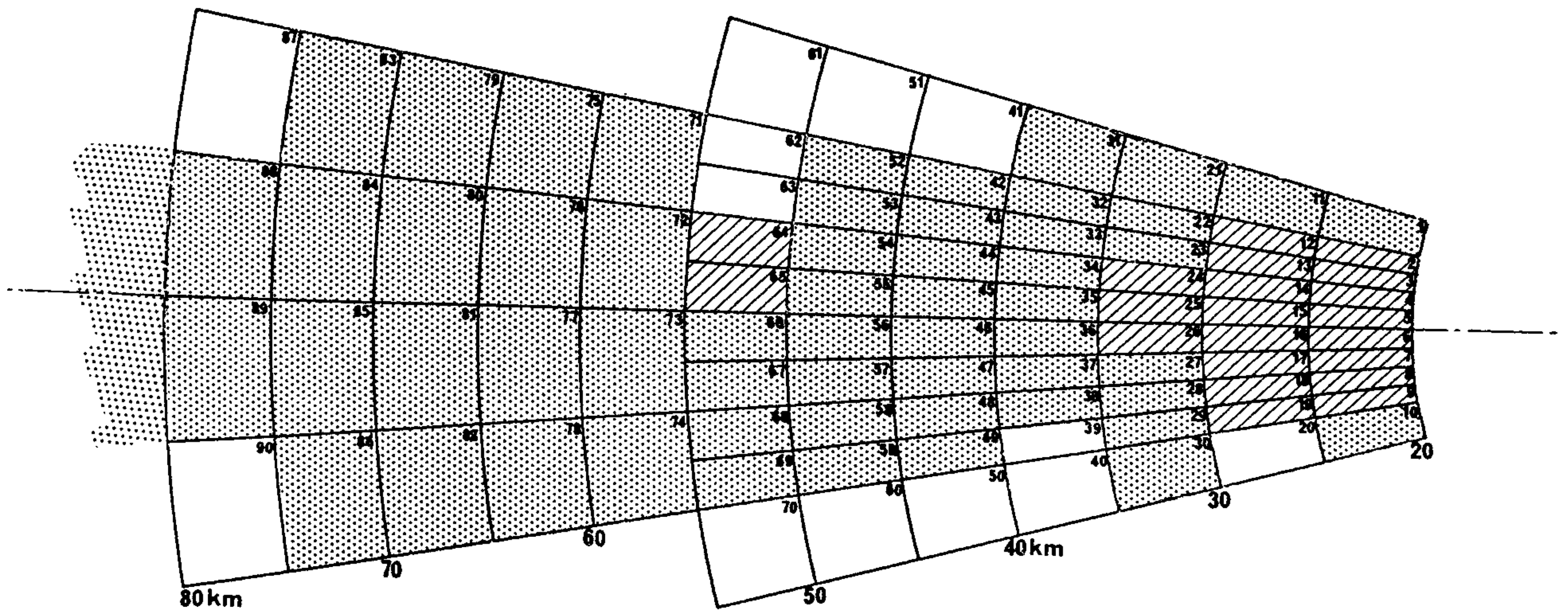


Fig. 8.3. BWR-2 case.
Sectors that are proposed decontaminated.

fire-hosing of roads

digging of gardens

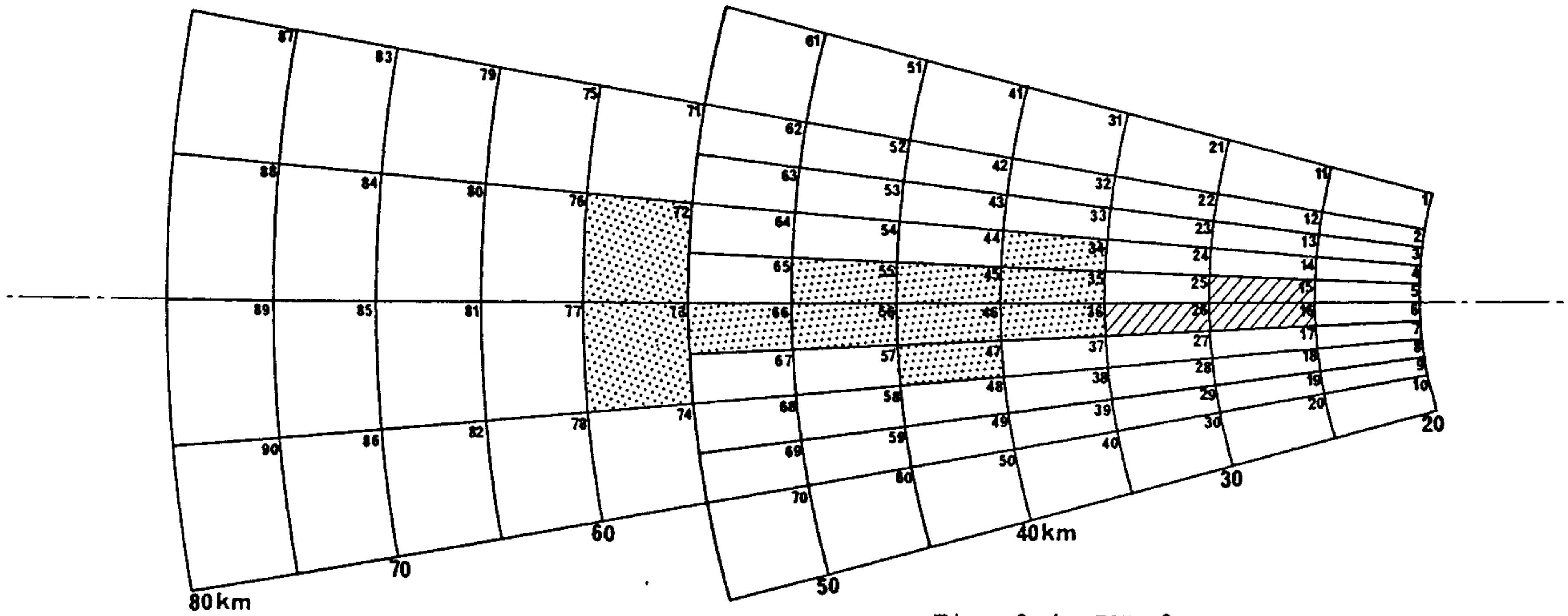


Fig. 8.4. BWR-3 case.
Sectors that are proposed decontaminated.

fire-hosing of roads

digging of gardens.

ly this is a simplified conception. In reality, the areas would be far more differentiated, but the total result is assumed to be largely similar.

Figures 8.5, 8.6, 8.7, and 8.8 show the reduced individual doses obtained in, respectively, the 1st, 2nd and 3rd month, and in a period of thirty years following the accident in the BWR-2 case. The total collective dose over 30 years in the area ranging up to 110 km from Barsebäck amounts to approximately 18 Mmanrem. As mentioned in 8.3.2, this dose can be reduced to about 15 Mmanrem if the population is relocated from areas so long as the individual dose here exceeds 3 rem per month.

8.4.2. Radiation doses to decontamination workers

It is necessary to know the dose rate out of doors as a function of time in order to calculate the doses received by decontamination workers. Figure 8.9 shows this dose rate for the BWR-2 case in the different sectors at t = 1 day after the accident. The shielding provided by the surrounding buildings as well as the lesser deposition on hard surfaces (buildings and roads) are taken into account. Figure 8.10 shows the relative dose rate from deposited activity after the accident in the BWR-2 case. Figure 8.12 shows the dose rates in the sectors at t = 14 days after the accident.

Calling the dose rate $\dot{D}(t)$ $[\mathrm{rem \cdot d^{-1}}]$, the time for the initiation of decontamination procedures T_e, and the time for the termination of decontamination T, both measured in relation to 1 day after the accident, the accumulated dose for a person working eight hours a day in the period from T_e to T is the following:

$$D(T_e, T) = \frac{1}{3} \int_{T_e}^{T} \dot{D}(t)dt \quad [\mathrm{rem}]$$

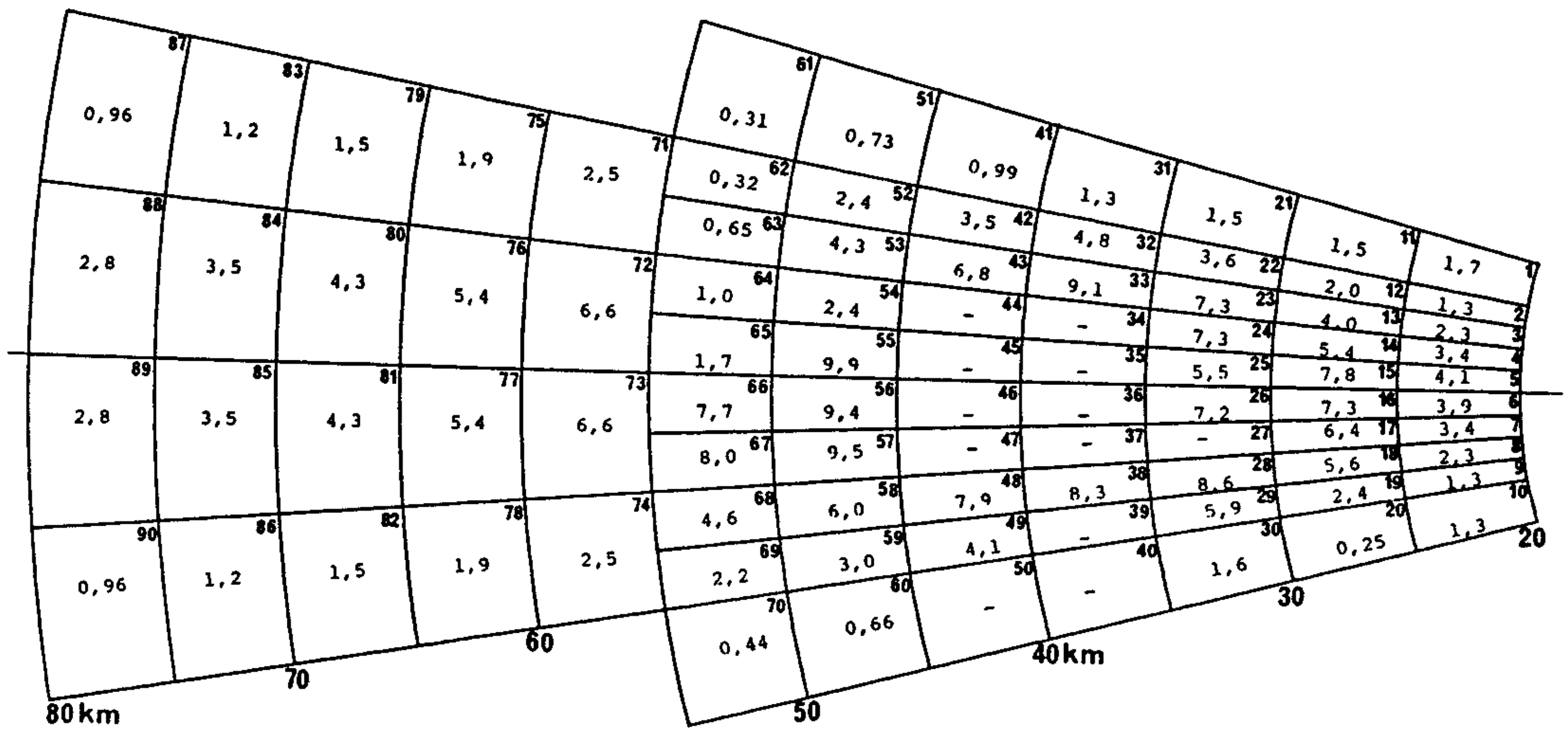


Fig. 8.5. BWR-2 case with dose-reducing measures. Individual doses (rem) in the first month. Relocation criterion 10 rem/month.

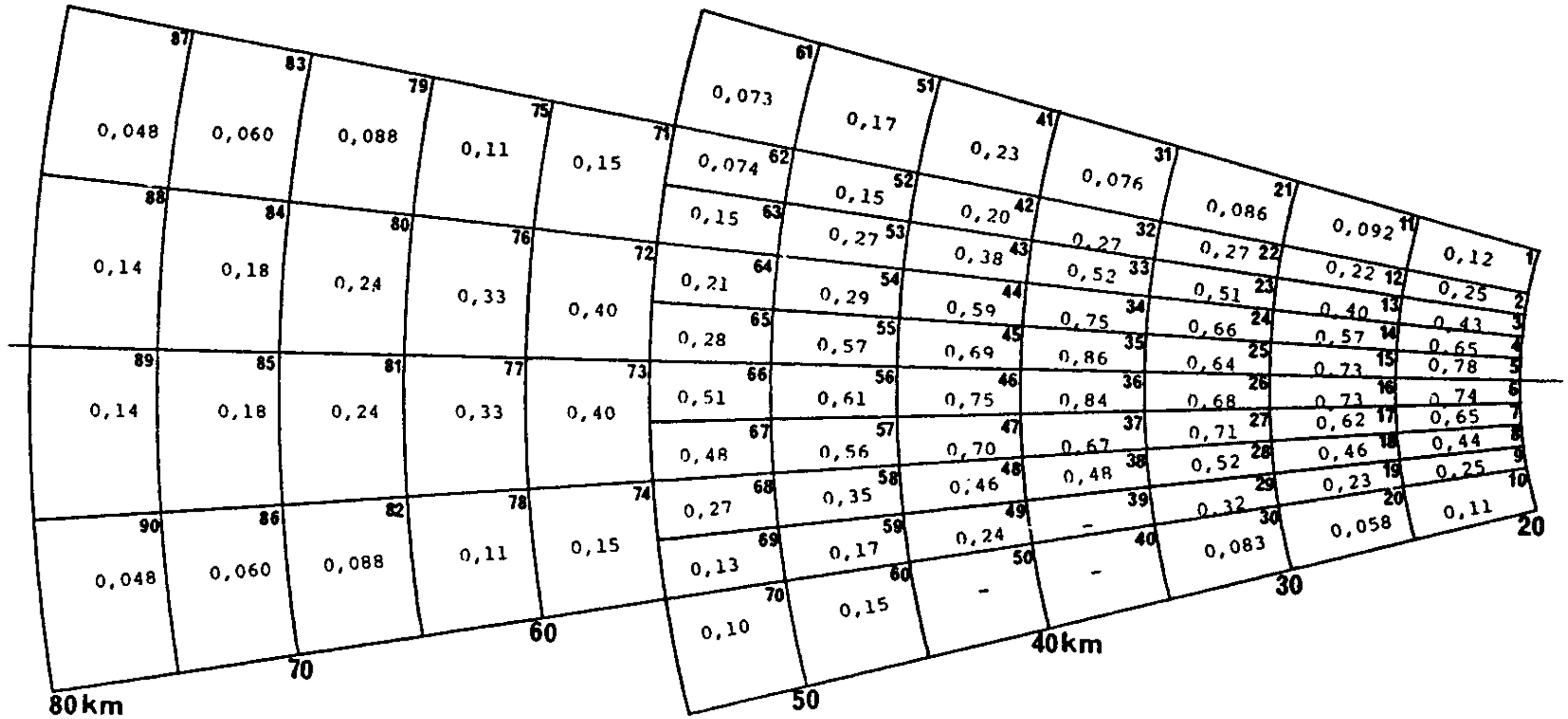


Fig. 8.6. BWR-2 case with dose-reducing measures. Individual doses (rem) in the second month. Relocation criterion 10 rem/month.

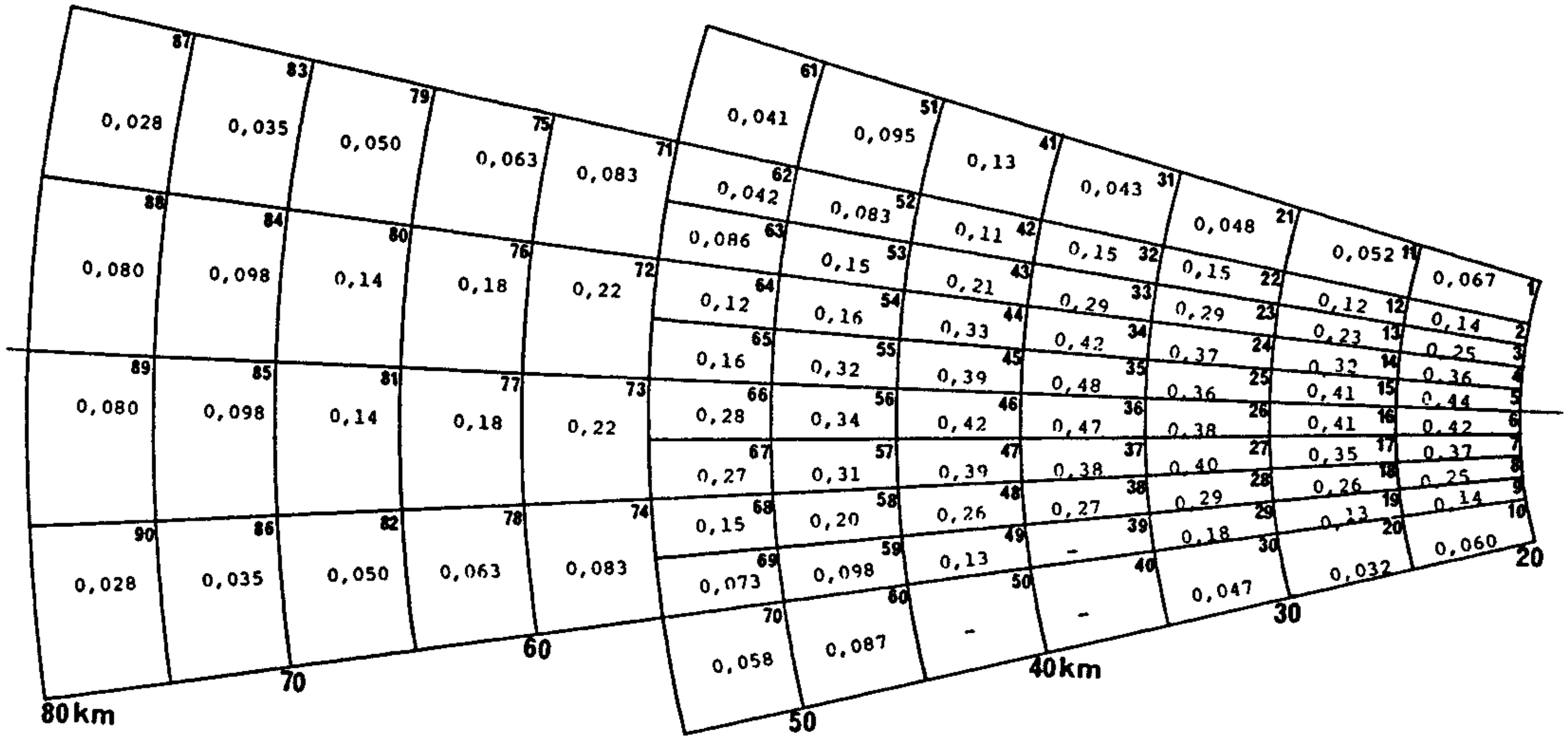


Fig. 8.7. BWR-2 case with dose-reducing measures.
Individual doses (rem) in the third month.
Relocation criterion 10 rem/month.

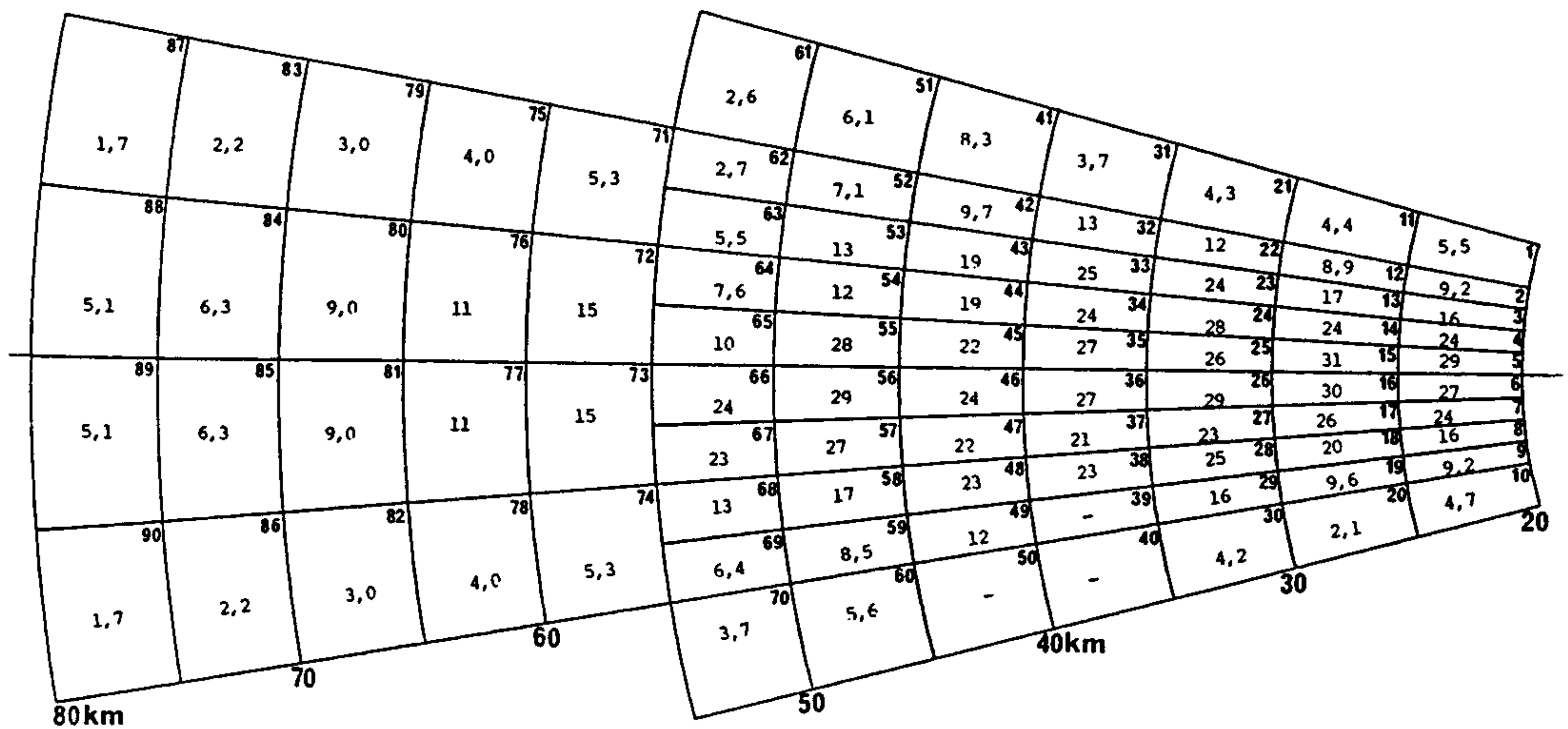


Fig. 8.8. BWR-2 case with dose-reducing measures.
Individual doses (rem) over 30 years.
Relocation criterion 10 rem/month.

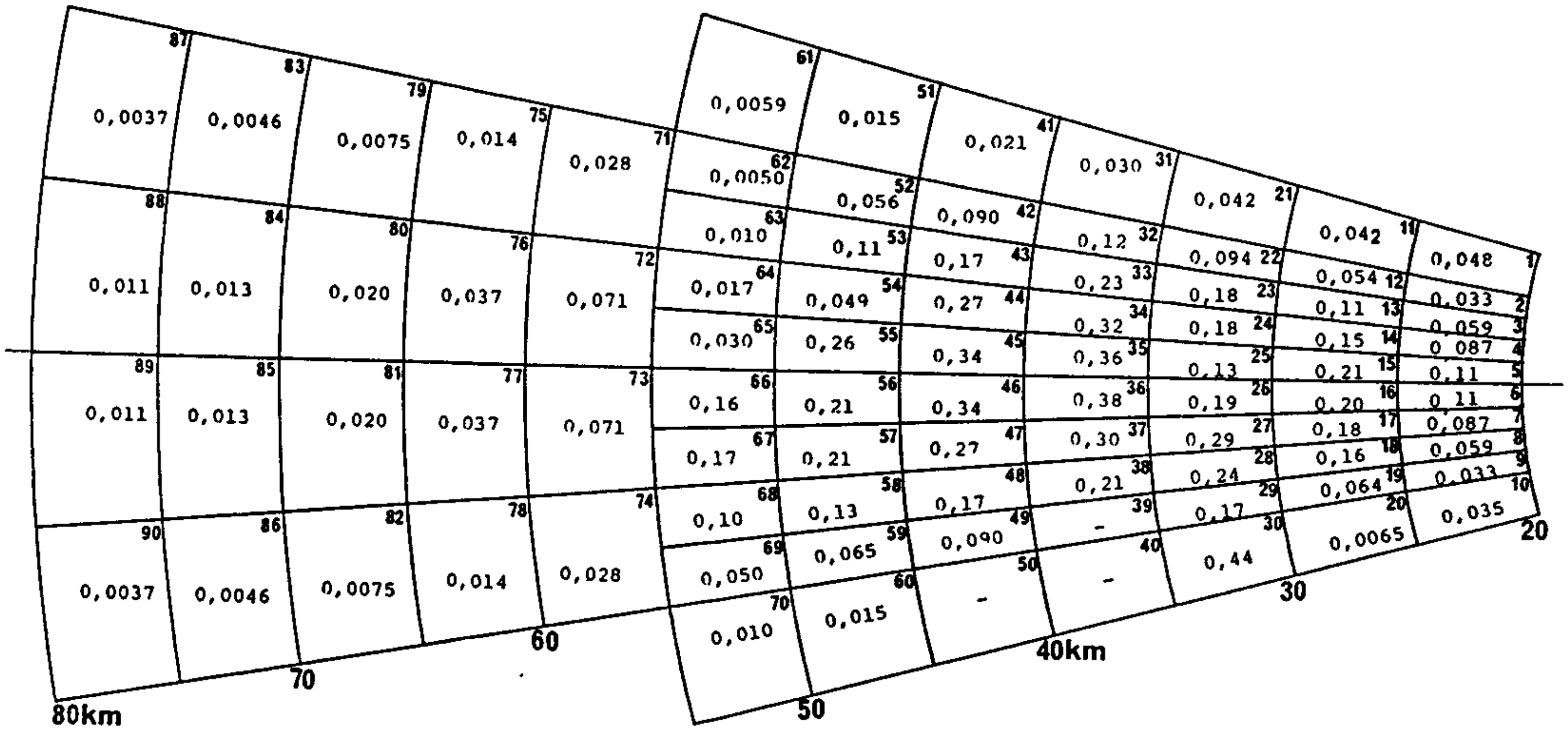


Fig. 8.9. BWR-2 case:
Dose rates out of doors (rem/hour)
24 hours after the accident.

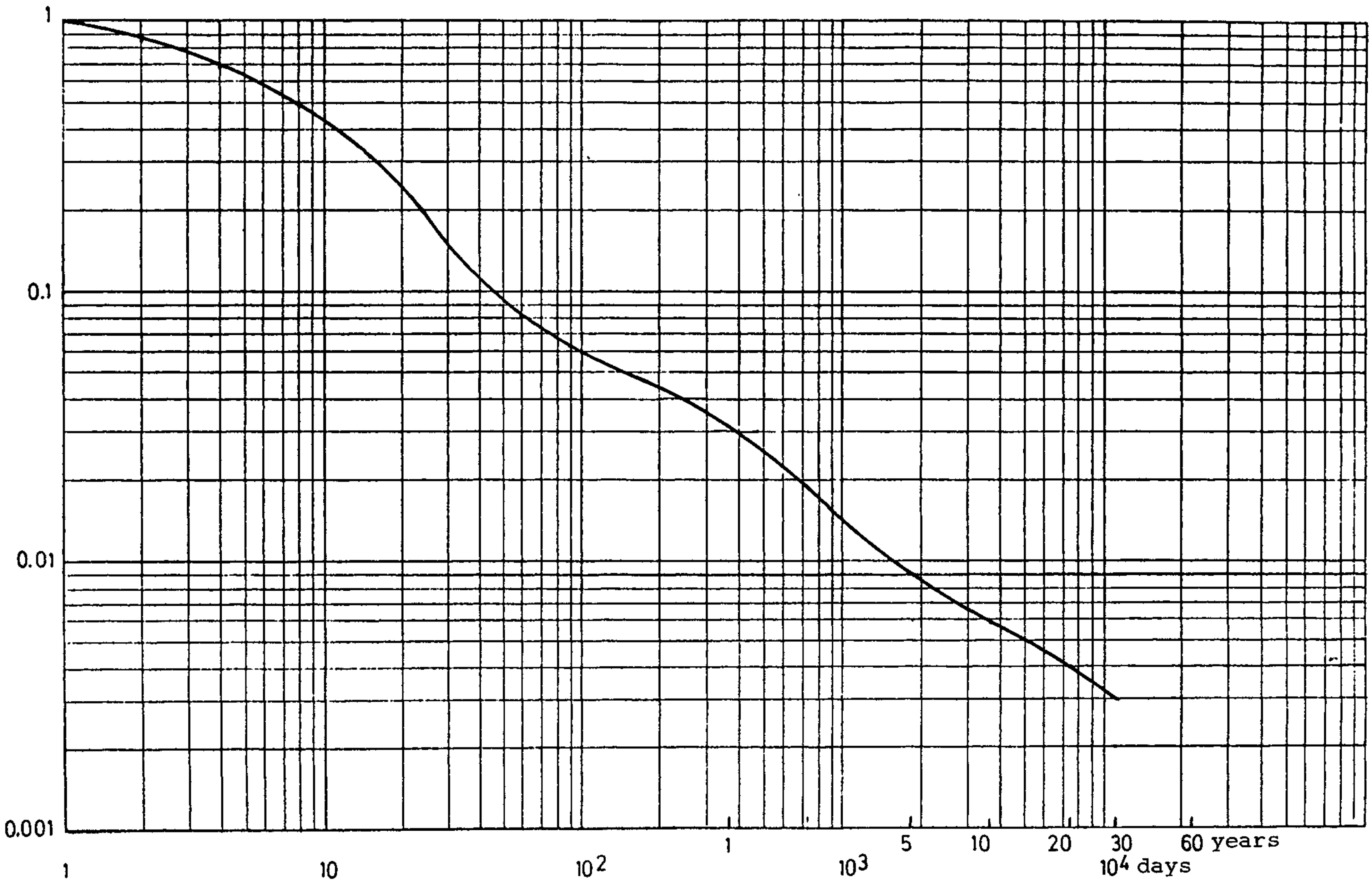
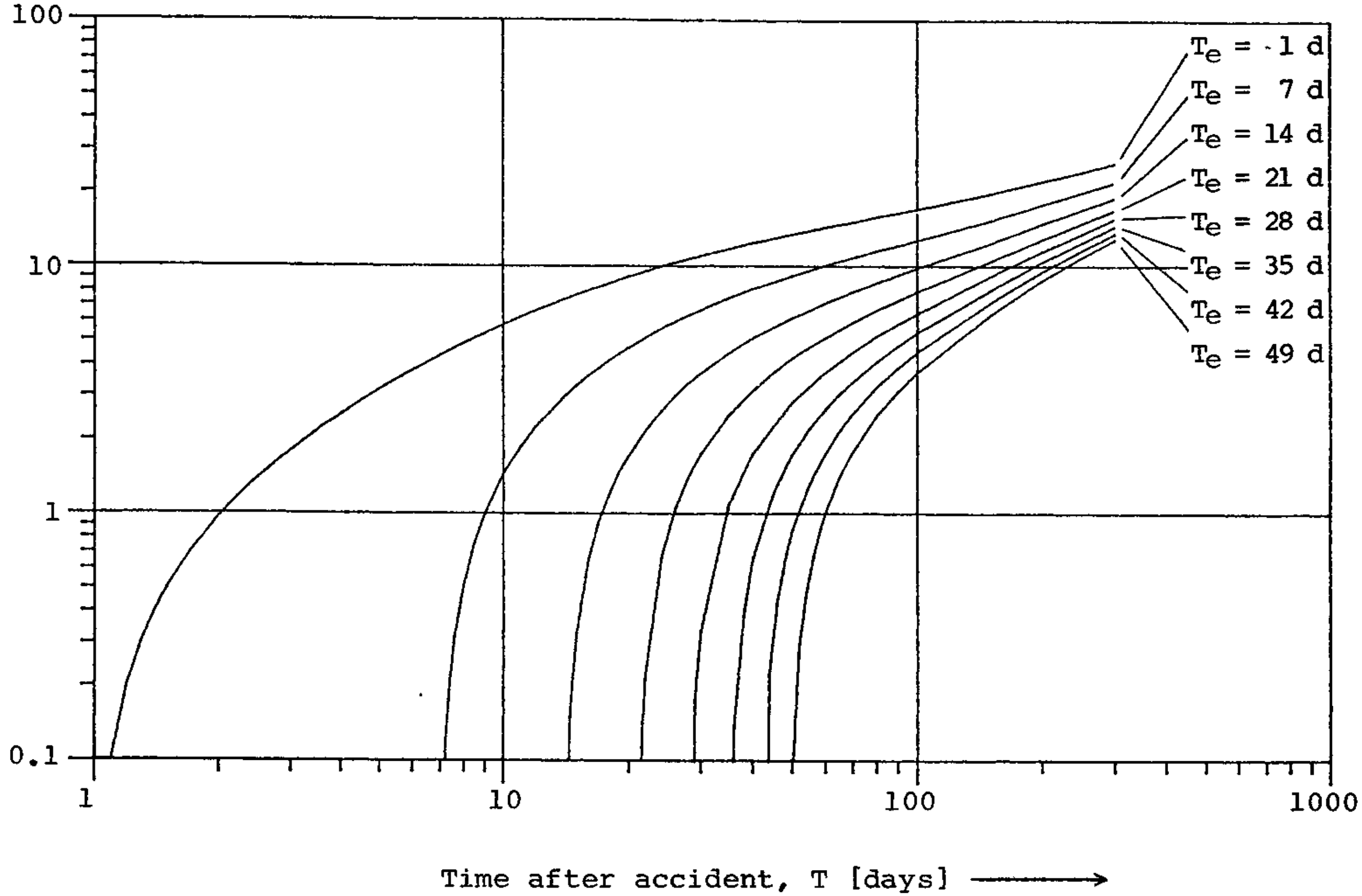


Fig. 8.10. BWR-2 case: Relative dose rate as function of time.



<u>Fig. 8.11.</u> Accumulated relative dose for different times of return for the relocated population T_e.

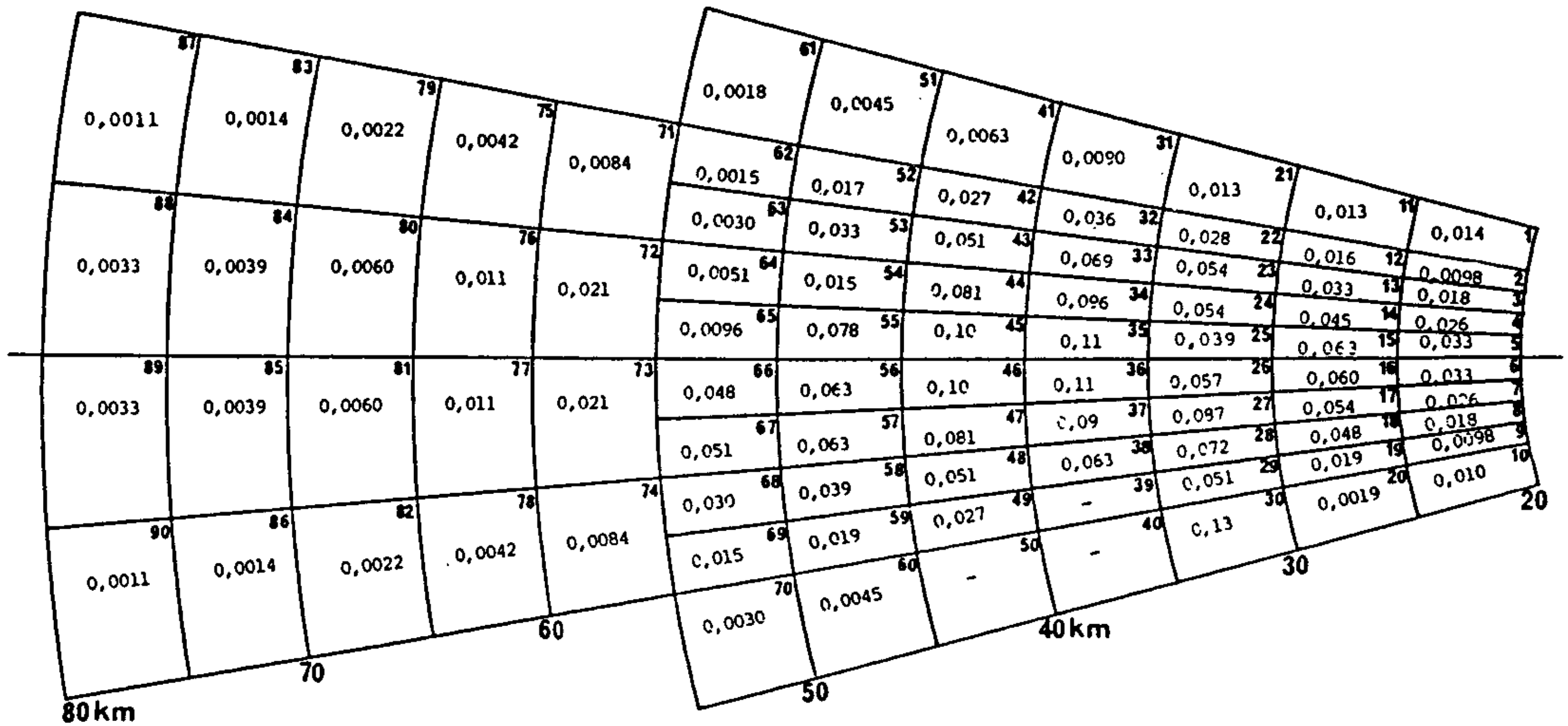


Fig. 8.12. BWR-2 case
Dose rates out of doors (rem/hr)
14 days after the time of the accident.

Figure 8.11 shows $D(T_e,T)$ as function of T for the BWR-2 case and different values of T_e. $\dot{D}(t)$ is here the relative dose rate from fig. 8.10 which is fitted to a sixth-degree logarithmic polynomial in these calculations. The absolute value of $D(T_e,T)$ for the areas in question is obtained through multiplication by the values shown in fig.8.9.

8.4.2.1. Collective dose from road hosing. According to the Civil Defence authorities, a group of ten men can hose 0.8 km of road during an eight-hour working day. The hosing of L km roads during, respectively, 14 and 60 days requires:

14 days: $0.89 \cdot L$ [workers]

60 days: $0.21 \cdot L$ [workers]

According to fig. 8.11, the following accumulated doses (relative) are obtained for uninterrupted location throughout, respectively, 14 and 60 days:

$$D(T_e = 14d,\ T = 14d + 14d) = 1.1$$

$$D(T_e = 14d,\ T = 14d + 60d) = 2.7\ .$$

Calling the dose rate at t = 1 d, D_{1d} [$\mathrm{rem \cdot d^{-1}}$], the collective dose for hosing 1 km of road for the two time intervals is then:

$$\Sigma D = 0.98 \cdot \dot{D}_{1d} \quad [\mathrm{manrem/km}]$$

for hosing taking 14 days, and

$$\Sigma D = 0.57 \cdot \dot{D}_{1d} \quad [\mathrm{manrem/km}]$$

for hosing taking 60 days.

Table 8.2 shows the collective doses per km road for the areas where hosing - cf. fig. 8.3 - is carried out. It is here assumed that the hosing of the entire area in question is carried out from t = 14 d to t = 28 d. If the hosing is carried out over a longer period of time, the collective dose is smaller.

The length of the road system in the areas to be hosed was calculated on the basis of data from the Danish Statistical Yearbook for 1980, combined with an assumption that the roads are uniformly distributed over the area of the municipalities. There is a total of 1400 km road in the areas affected. The total collective dose to the workers doing the hosing, based on the data in table 8.2, is found to be approximately 3000 manrem.

It should be noted that the calculations do not take into account the fact that the dose rate gradually falls as decontamination progresses.

<u>8.4.2.2. Collective doses from digging the gardens of houses in residential areas</u>. It is assumed that it takes 14 man-days to dig one plot of 700 m^2 in size - that used in these calculations. It is further assumed that the majority of these plots are dug in the 5th and 6th week following the accident, which interval of time is considered representative of the entire semi-urban area.

According to fig. 8.11, the following accumulated relative dose is obtained:

$$D(T_e = 28d,\ T = 42d) = 0.63$$

The collective dose from digging the gardens can then be calculated from:

$$\Sigma D = \dot{D} = 0.63 \cdot \dot{D}_{1d} \quad [\text{manrem/garden}]$$

Table 8.2. Collective doses [manrem] for decontamination in the BWR-2 case, cf. fig. 8.3

Sector no.	Number of gardens	Collective doses Digging	Collective doses Hosing per km road	Sector no.	Number of gardens	Collective doses Digging	Collective doses Hosing per km road
1	2090	1517		46	1122	5768	
2			0.78	47	1109	4527	
3			1.39	48	1106	2843	
4			2.05	49	1106	1505	
5			2.59	50			
6			2.59	51	856	194	
7			2.05	52	733	621	
8			1.39	53	835	1389	
9			0.78	54	157	116	
10	385	204		55	1023	4022	
11	3421	2172		56	927	2943	
12			1.27	57	1236	3925	
13			2.59	58	1203	2365	
14			3.53	59	1128	1109	
15			4.94	60	2141	486	
16			4.70	61	520	46	
17			4.23	62			
18			3.76	63			
19			1.51	64			0.40
20				65			0.71
21	4359	2768		66	641	1551	
22	1687	2398		67	518	1331	
23	1770	4817		68	1067	1613	
24			4.23	69	1183	894	
25			3,06	70	1695	256	
26			4.47	71	3271	1381	
27	1695	7432		72	807	864	
28	2119	7689		73	852	912	
29	2826	7264		74	1508	637	
30	5651	3759		75	420	90	
31	2345	1064		76	813	456	
32	1636	2968		77	1320	740	
33	1636	5689		78	1721	369	
34	1445	6991		79	696	79	
35	1277	6951		80	982	297	
36	1338	7688		81	191	58	
37	1216	5516		82	1041	118	
38	1138	3613		83	831	58	
39				84	298	60	
40				85	313	63	
41	1295	411		86	574	40	
42	934	1271		87	208	12	
43	934	2401		88	215	35	
44	934	3813		89	215	35	
45	1043	5362		90	4559	253	

Table 8.2 shows the distribution of free-standing houses in the semi-urban area. The distribution is based on a survey made by the Bureau of Statistics of free-standing houses in municipalities of the metropolitan area, as well as on the distribution of the area of the municipalities over the different sectors.

If the number of houses inside a given sector is multiplied by the dose given above for the digging of one garden, then the collective dose for the whole of the area in question is obtained. Table 8.2 shows the distribution of collective doses over the individual sectors. Once again, the fact that dose rate gradually decreases as decontamination progresses is not taken into account. The total collective dose from digging about 100 000 gardens surrounding houses is approximately 140 000 manrem.

8.5. Costs

The plans for and the costs associated with a population relocation were prepared by the Civil Defence authorities for Greater Copenhagen. The costs are about 450 000 Danish kroner per 1000 persons. For billeting, a further approximately 80 000 kroner per 1000 persons is needed for a one-week period.

The manpower required to hose 1400 km of road is approximately 17 000 man-days of 8 hours.

The manpower necessary for digging the gardens is estimated to be some 1 million man-days of 8 hours.

8.6. Conclusion

Based on Risø's experimental and theoretical investigations regarding different dose-reducing measures, it can be concluded that it would hardly be possible with reasonable efforts to reduce the external radiation doses from deposited activity by more than a factor 2-5. WASH-1400 gives reduction factors of 10-20.

In the BWR-2 case, the collective dose on Danish territory over the following 30 years could amount to approximately 41 Mmanrem if no dose-reducing measures are carried out. A combined hosing of roads in urban areas, digging of gardens, and a temporary relocation of the population for one month from areas where the first month dose exceeds 10 rem, reduces the collective dose to about 18 Mmanrem. The collective dose to decontamination workers would total approximately 0.1-0.2 Mmanrem. After decontamination, the average individual dose in the most heavily contaminated sector would not exceed approximately 30 rem over the 30 years following the accident.

8.7. References

Cl 63 Clark, D.E. et al., 1963, "Removal effectiveness of simulated dry fall-out from paved areas by motorized and vacuumized street sweeperes", USNRDL-TR-746, U.S. Naval Radiological Defence Laboratory.

Di 61 Dick, J.L. et al., 1961, "Monitoring and decontamination technique for plutonium fallout on large-area surfaces", WT-512, Air Force Special Weapons.

He 79 Hedemann Jensen, P., 1979, "Dæmpningsfaktorer for gammastråling fra deponeret aktivitet opnået ved pløjning af jord og asfaltpålægning af veje" (Attenuation factors for gamma radiation from deposited activity obtained by ploughing the soil and applying new asphalt to roads). Risø work report.

He 82 Hedemann Jensen, P., 1982, "Shielding factors for gamma radiation from activity deposited on structures and ground surfaces", Risø-M-2270 (in preparation).

Ro 81 Roed, J., 1981, "Overfladedeponering af luftbåret materiale frigjort ved kernenedsmeltningsuheld i kraftreaktorer" (Surface deposition of airborne material released by a core-melt accident at a power reactor), Risø-M-2274.

Ro 82 Roed, J., 1982, "Reduktion af dosis ved nedpløjning af gamma-aktive isotoper" (Reduction of doses from gamma-active isotopes by ploughing), Risø-M-2275 (in preparation).

Wa 82 Warming, L., 1982, "Weathering and decontamination of radioactivity deposited on asphalt surfaces", Risø-M-2273 (in preparation).

Wi 65 Wiltershire, L.L. et al., 1965, "Removal of simulated fallout from asphalt street by firehosing techniques", U.S. Naval Radiological Defense Laboratory.

Wi 66 Wiltershire, L.L. et al., 1966, "Three tests of firehosing technique and equipment for the removal of fallout simulant from asphalt street and roofing materials", USNRDL-TR-1048, U.S. Naval Radiological Defense Laboratory.

9. INDIVIDUAL DOSES FROM WORK CARRIED OUT IN THE CONTAMINATED AREA

9.1. Introduction

Perhaps the contamination after a core-melt accident would be so serious that businesses, schools, institutions, etc., would have to be closed for a shorter or longer period of time. Because of the better shielding generally provided by the structures housing such institutions, those that might have to be closed would be in areas where the residential population had been relocated. For this reason, a calculation was made of the doses that people would receive if spending their non-working hours outside the contaminated area, but working a 40-hour week in a certain sector; transport to and from work is assumed to take place in the same sector. Furthermore, an evaluation was made of the effect that the combination of decontamination measures (cf. section 8.4) would have on the individual doses from work and transport in these sectors.

While the individual would find it a great nuisance to be relocated from home for a short period of time, for society as a whole this intervention would have reasonable consequences. On the other hand, it is of great importance for society to keep places of work in operation, whether these be private businesses, or public offices and institutions. Thus it is obvious that the criteria applicable to the relocation of residential areas should be far stricter than those used for the closure of places of work, naturally assuming that both lie well below the level where there is risk of non-stochastic health effects. The Working Group chose to use the same dose criteria for a week's work as for a month's "normal" residence. Therefore in the following the criteria 3 rem/week and 10 rem/week are considered for the closure of places of work and institutions, cf. section 8.3.2.

9.2. Radiation doses from work and transport in contaminated areas that are not decontaminated

For the calculation of radiation doses from deposited activity for work and transport in contaminated areas, use was made of the following time-averaged shielding factors for municipalities, cf. chapter 6, table 6.2:

- urban districts
  $23.8\% \times 0.015 \times 0.1 + 5\% \times 0.25 \times 0.1 = 0.0016$

- non-urban districts
  $23.8\% \times 0.015 \times 0.1 + 5\% \times 0.25 = 0.013$

The shielding factors here derived for the individual sectors are given in table 7.1 in chapter 7.

Figures 9.1 and 9.2 show the individual doses alone for work and transport in, respectively, the first week and over thirty years following an accident such as that in the BWR-2 case, assuming that no decontamination has taken place.

The largest individual dose in the first week is then approximately 1 rem, and over the first 30 years, approximately 20 rem.

Figures 9.3 and 9.4 show the corresponding individual doses in the BWR-3 case. The largest individual doses over the first week and over the first 30 years are, respectively, 0.3 rem and 3 rem.

In the BWR-2 case, the total collective dose from work and transport is approximately 7 Mmanrem, i.e., about 18% of the total collective dose from work, transport, location out of doors and location indoors.

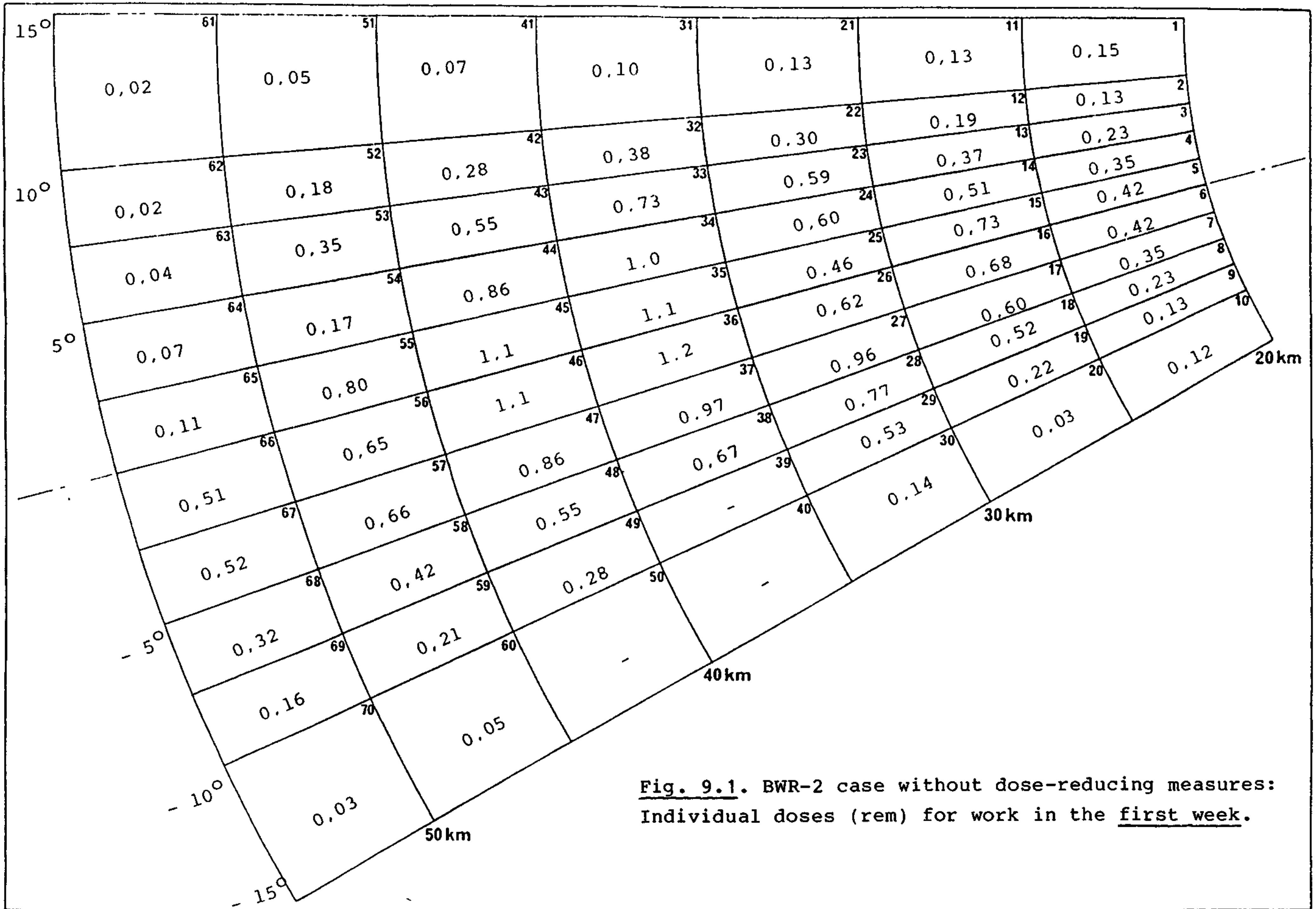


Fig. 9.1. BWR-2 case without dose-reducing measures: Individual doses (rem) for work in the first week.

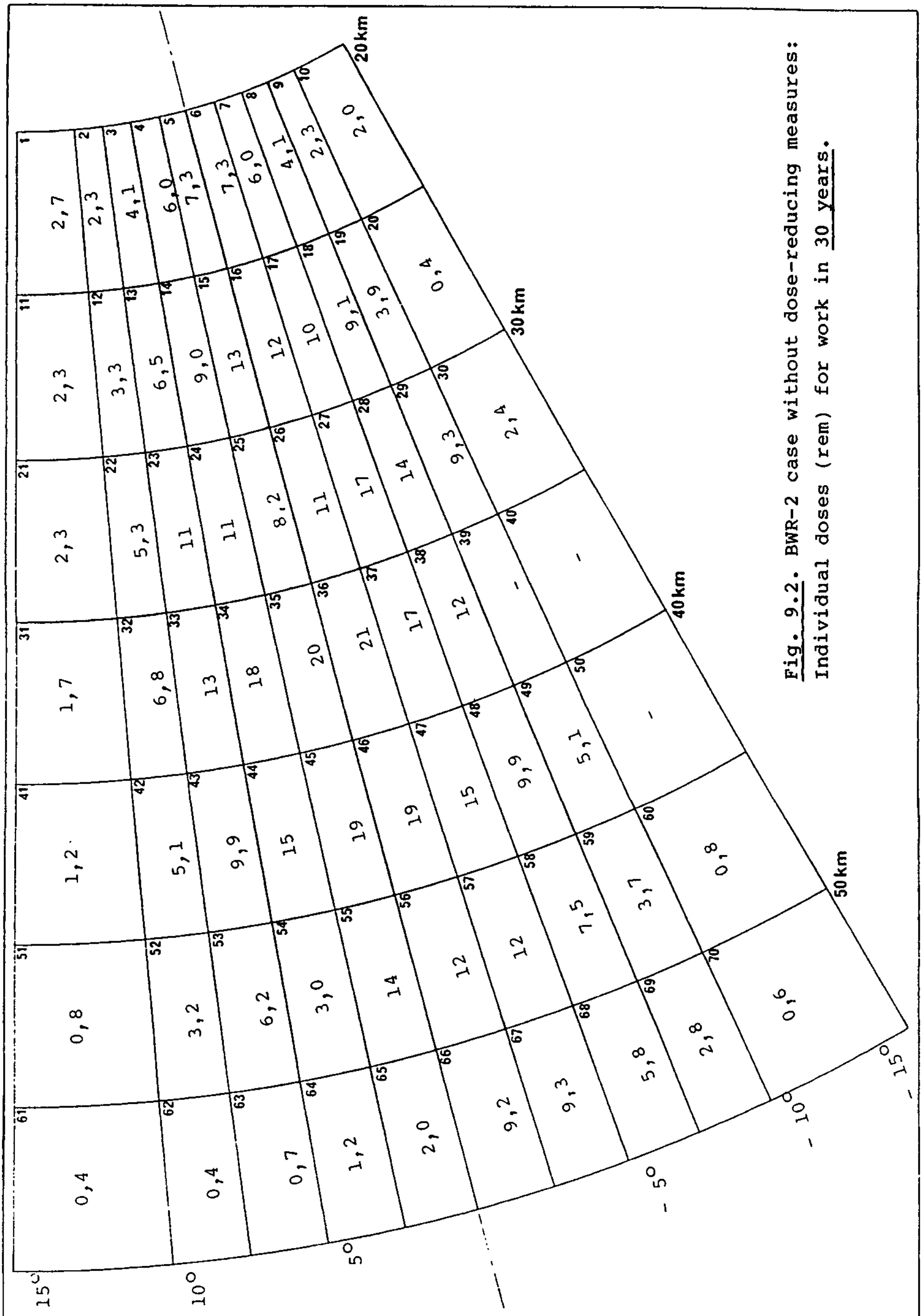


Fig. 9.2. BWR-2 case without dose-reducing measures: Individual doses (rem) for work in 30 years.

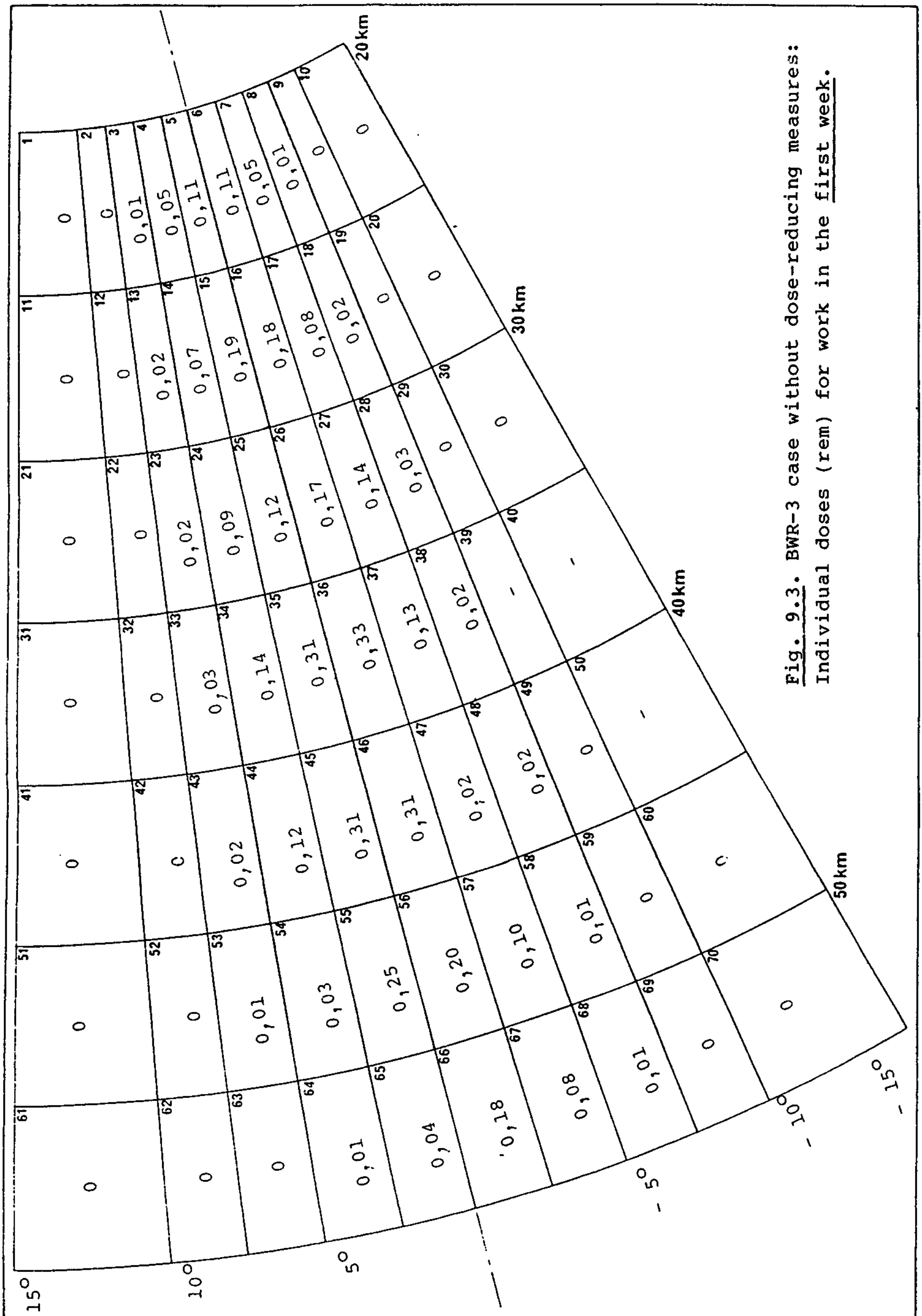


Fig. 9.3. BWR-3 case without dose-reducing measures: Individual doses (rem) for work in the first week.

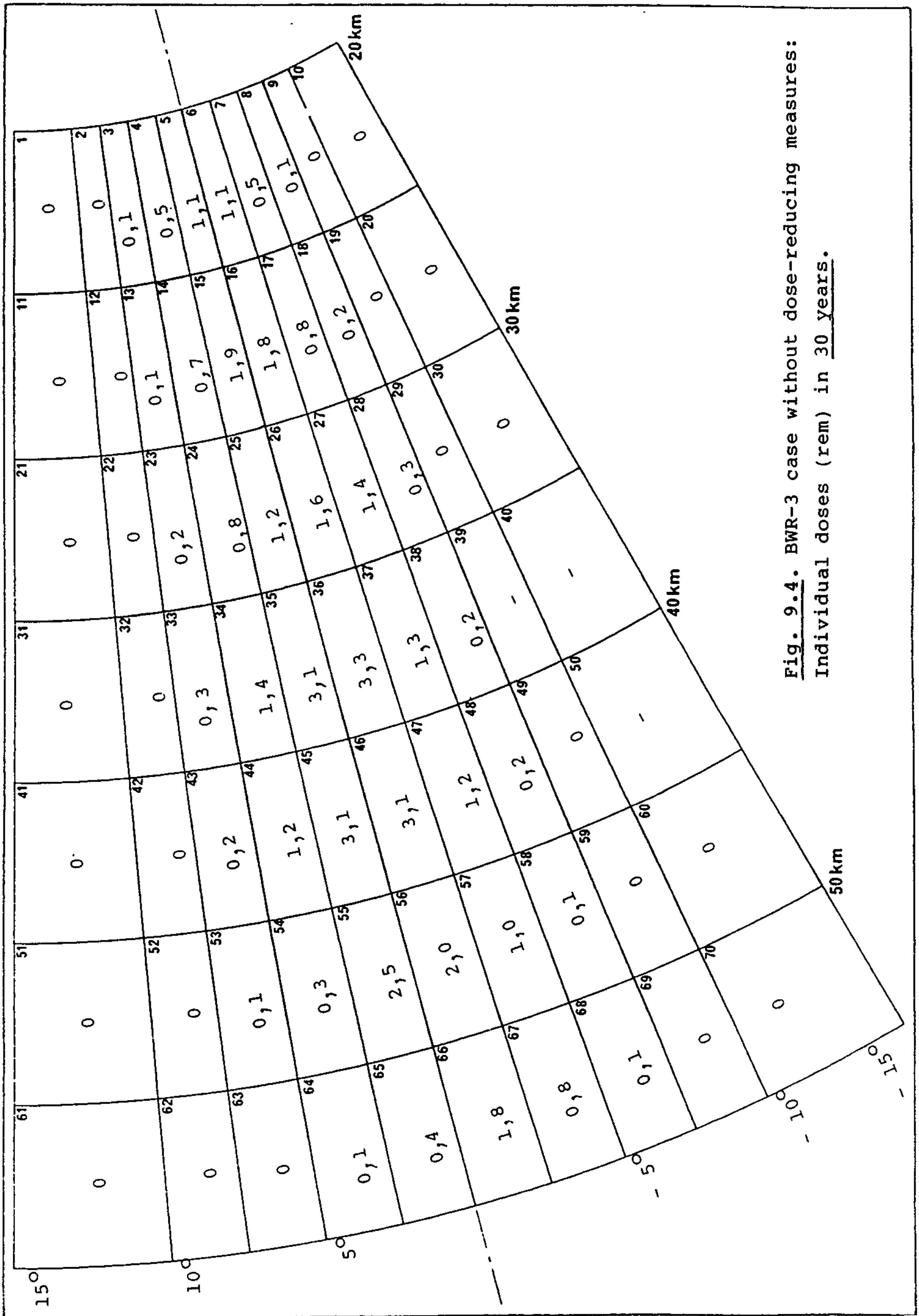


Fig. 9.4. BWR-3 case without dose-reducing measures: Individual doses (rem) in 30 years.

9.3. Radiation doses for work and transport in contaminated areas that are decontaminated

After decontamination procedures, as outlined in chapter 8, in the contaminated areas where the average dose over the second month exceeds 0.25 rem, the following time-averaged modified shielding factors are used for the two types of municipality, cf. chapter 8, table 8.1:

- urban areas
  23.8% × 0.0015 + 5% × 0.019 = 0.00131

- non-urban areas
  23.8% × 0.0015 + 5% × 0.0417 = 0.00244

Figure 9.5 shows the modified shielding factors (cf. section 8.3.1) for the individual sectors as they appear from distributing the modified shielding factors for the municipalities by simple area-weighting.

Figure 9.6 shows the individual doses for work and transport over 30 years following an accident like that in the BWR-2 case when decontamination (hosing and digging) takes place during the 2nd and 3rd week in areas where doses exceed 3 rem in the first month, and during the course of two months in other areas where doses exceed 0.25 rem in the second month. The largest individual dose over the first 30 years after the accident is then approximately 5 rem.

9.4. Conclusion

The total collective doses up to a distance of 110 km from Barsebäck for work and transport, with and without decontamination measures, as well as the collective dose for work and transport in the first month in the areas that are envisaged relocated applying a criterion of 10 rem per month, are shown for the BWR-2 case in the following table:

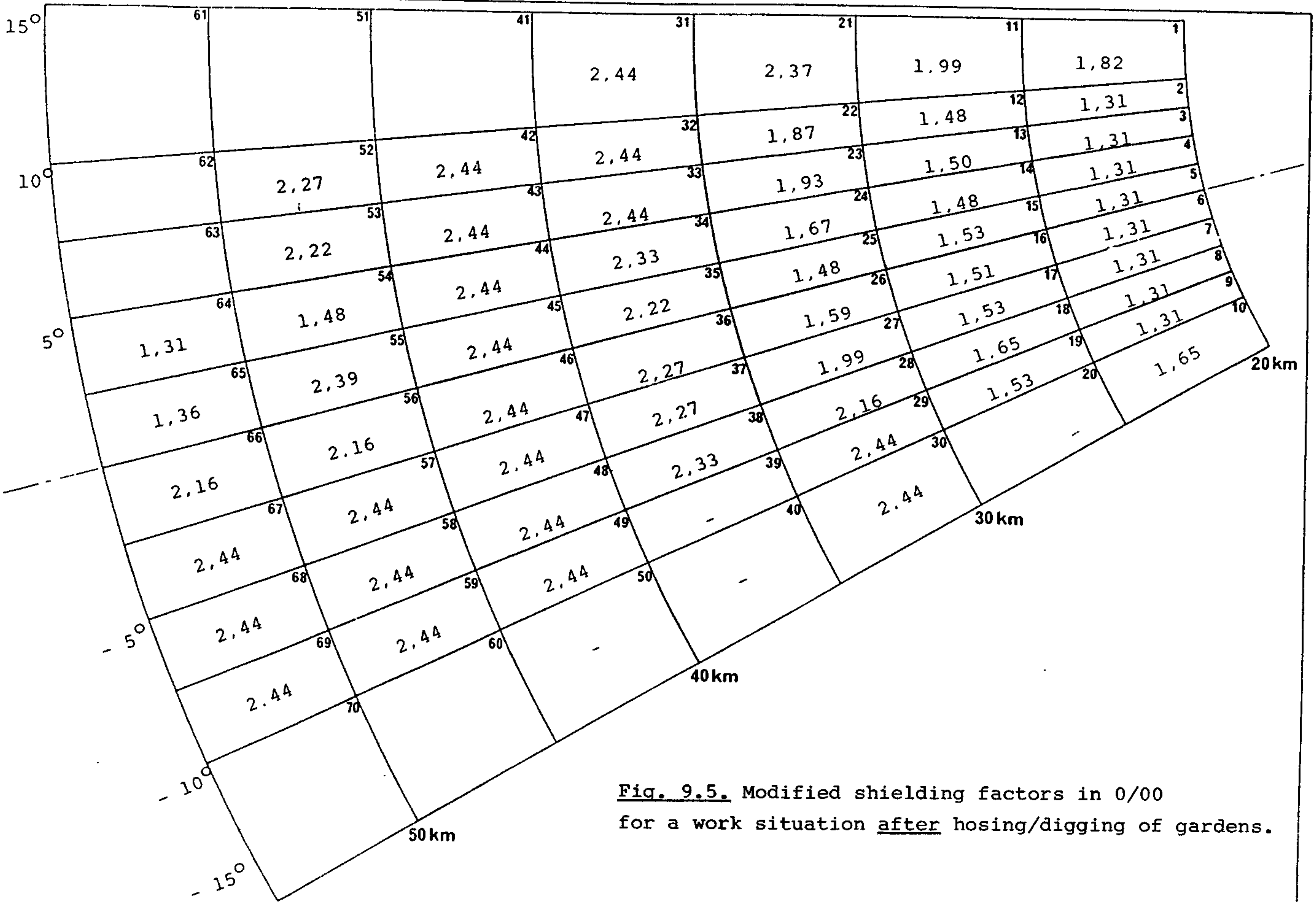
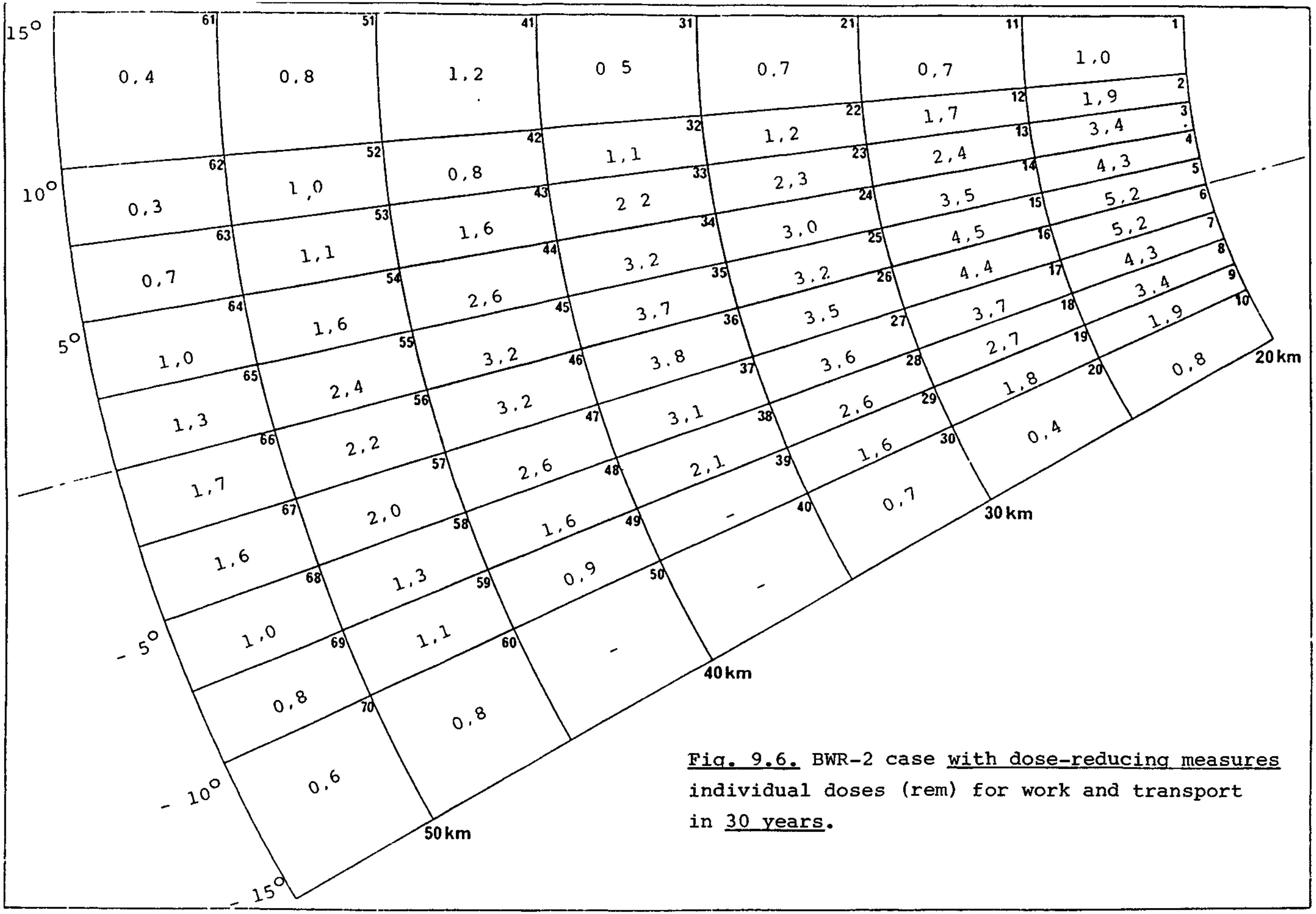


Fig. 9.5. Modified shielding factors in 0/00 for a work situation after hosing/digging of gardens.



<u>Fig. 9.6.</u> BWR-2 case <u>with dose-reducing measures</u> individual doses (rem) for work and transport in <u>30 years</u>.

	Collective dose (30 y) up to distance of 110 km	Collective dose (1 mth) in relocated areas
Reference situation	7.3 Mmandrem	0.2 Mmandrem
With a decontamination as described	2.6 Mmandrem	-

In the case of a rather slower decontamination, e.g., only areas where doses exceed 10 rem in the first month are decontaminated during the two weeks, the collective doses will be somewhat greater (in the given case 20%).

It can be seen that the collective dose from work and transport over 30 years, after a decontamination as described, constitutes approximately 20% of the total collective dose from being located alternately out of doors, inside the home, at work and during transport. This is largely the same percentage as in the reference situation where no decontamination is carried out and where normal activities are otherwise assumed.

Even when using a closure criterion of 3 rem/week, it would not be necessary to close down places of work or institutions on Danish territory after accidents like those termed BWR-2 and BWR-3 cases.

10. DOSE-REDUCING MEASURES RELATING TO THE PRODUCTION OF FOODSTUFFS

10.1. The production of foodstuffs in the contaminated area

Agricultural products

To calculate the production of foodstuffs and fodders, Zealand was arbitrarily divided up into a number of districts using a grid of 30° ring sectors, as shown on fig. 10.1. Sector 9 represents the direction that the radioactive cloud is assumed to take (see 7.2.1).

Using Danish agricultural statistics (Da 78), a calculation was made of agricultural production in the different districts. Tables 10.2-4 show the annual production in tons, of, respectively, vegetable foodstuffs, animal foodstuffs, and fodder materials. On this basis a calculation can be made of the average production per km^2 of land in the different districts.

Fish

Statistics (Da 77) show that the annual catch in the Sound is about 3000 t (1977). In the Kattegat the catch is about 150 000 t (1977) and in the area of the Belts and the Baltic some 35 000 t (1977). The total annual catch in Danish waters is 1.7 × 10^6 t, of which the main part is taken in the North Sea.

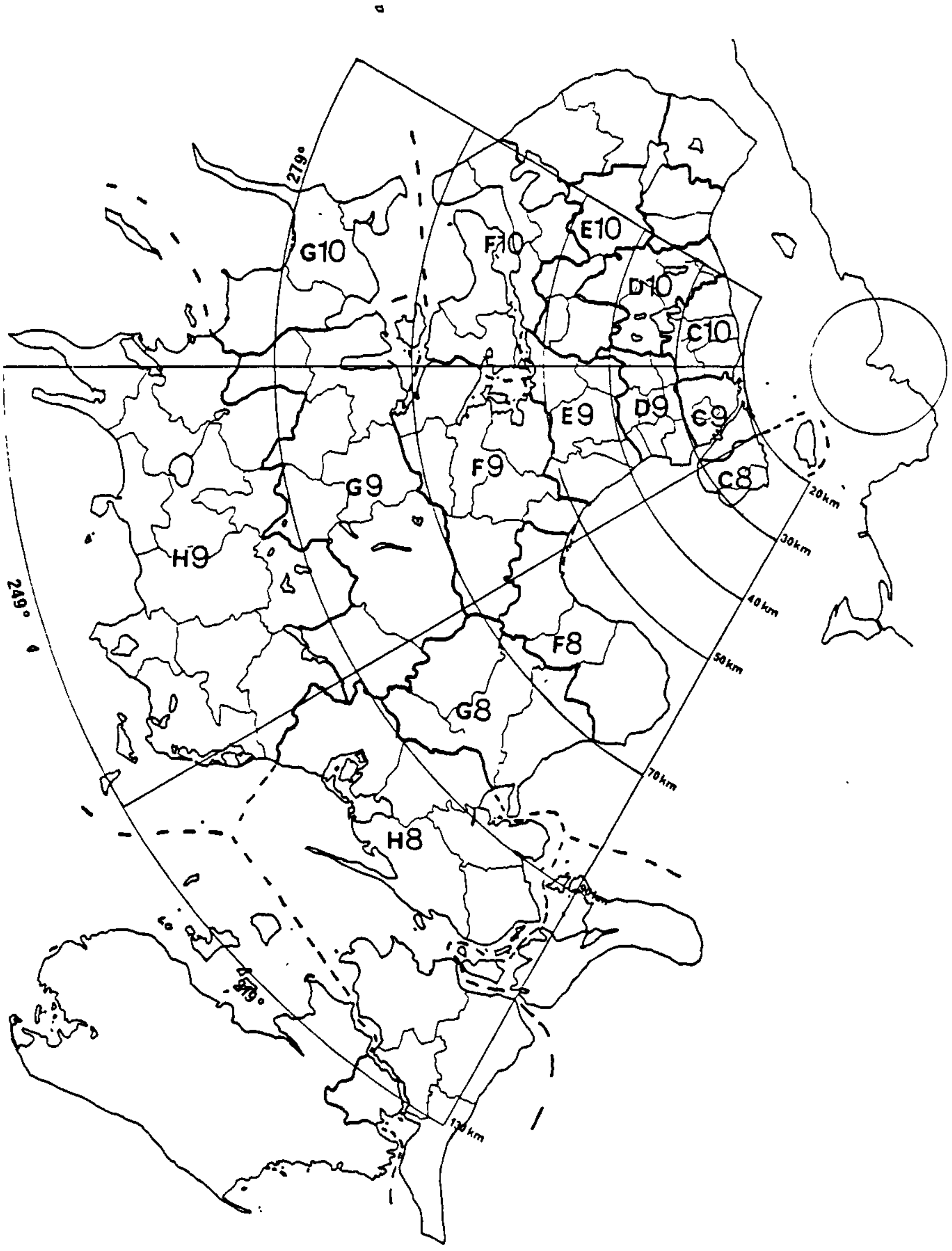


Fig. 10.1. Survey of the districts.

Table 10.1. Annual production in tons of vegetable foodstuffs in the districts (cf. fig. 10.1)

District	Wheat	Rye	Oats	Potatoes	Roots	Leaf vegetables	Fruit	Soft fruit
C8	523	219	58.6	1 407	404	1 565	688	66.1
C9	-	-	-	-	1.5	5.7	2.5	0.2
C10	2 360	113	29.7	101	94.6	367	161	15.5
D9	1 080	452	119	88.8	136	527	232	22.2
D10	1 620	1 180	702	1 990	388	674	1 640	174
E9	9 930	3 200	1 170	1 600	719	2 340	1 180	104
E10	3 950	3 100	1 920	8 300	338	556	1 470	156
F8	18 800	3 770	5 320	1 550	937	1 830	1 440	139
F9	22 500	5 320	2 810	3 260	942	2 340	1 480	113
F10	6 570	5 150	3 200	27 800	339	558	1 480	156
G8	22 000	4 810	3 540	655	1 220	767	682	140
G9	38 500	13 311	8 270	4 380	8 730	3 960	2 330	795
G10	10 300	4 010	2 400	1 740	11 600	5 030	2 720	1 030
H8	55 100	9 580	7 840	2 270	3 800	4 500	5 670	719
H9	54 500	21 200	12 700	16 000	13 800	6 000	3 240	1 220

Table 10.2. Annual production in tons of animal products in the districts (cf. fig. 10.1)

District	Pork	Beef and veal	Natural milk	Eggs
C8	2.7	6.9	51.9	19.6
C9	-	-	-	-
C10	25.7	46.5	407.0	19.1
D9	75.2	7.4	40.7	29.4
D10	577	107	1 570	49
E9	2 450	271	3 380	532
E10	2 240	648	10 200	479
F8	11 100	968	17 400	1 020
F9	10 200	1 400	24 200	761
F10	5 010	1 320	19 900	704
G8	10 300	1 330	22 800	396
G9	26 900	3 700	64 600	1 970
G10	7 420	1 170	19 400	88
H8	23 200	3 760	68 500	2 460
H9	44 800	5 430	92 900	1 830

Table 10.3. Annual production in tons of vegetable fodder materials in the districts (cf. fig. 10.1)

District	Barley and mixed grain	Straw	Roots	Roots (tops)	Grass and green fodder
C8	1 950	1 050	1 880	950	3 320
C9	-	-	-	-	-
C10	1 010	540	140	70	6 140
D9	4 040	2 170	120	60	2 850
D10	11 200	6 300	4 140	1 920	31 500
E9	41 300	19 600	9 200	4 900	40 400
E10	29 900	16 800	17 700	8 200	73 600
F8	75 300	28 600	53 200	27 200	86 400
F9	102 000	43 700	54 800	29 600	139 000
F10	50 000	28 000	60 000	27 500	107 000
G8	87 600	33 300	75 000	37 600	109 000
G9	193 000	92 500	173 000	91 800	333 000
G10	55 400	27 900	56 800	30 800	119 000
H8	199 000	66 300	649 000	318 000	275 000
H9	293 000	147 000	523 000	283 000	411 000

10.2. Relevant radionuclides associated with the contamination of foodstuffs in the BWR-2 case

The radio-ecological significance of a radionuclide depends on what amount of it is released and on its transfer factor from release to the foodstuff concerned. Even if a radionuclide can be transferred to foodstuffs, it is not always certain that it is of importance for the dose. This depends on the radiobiological properties of the radionuclide - these being expressed by the ALI value (annual limit of intake - the exact definition is given in ICRP 79).

The amount of activity released depends on the inventory in the reactor core at the time of the accident and on the circumstances of the accident, cf. chapter 3, tables 3.1 and 3.2.

Investigations of radioactive fallout from nuclear weapons testing (Aa 79) have provided knowledge of the transfer factors (pCi kg^{-1} y (mCi $km^{-2})^{-1}$) from deposition to the majority of Danish foodstuffs for radionuclides such as ^{90}Sr, ^{131}I and ^{137}Cs, i.e., under normal agricultural operations. As a result of consistently effected deep ploughing, transfer factors can be reduced by a factor of approximately 3 for ^{90}Sr in the year after the accident and the following years. It is ^{90}Sr, ^{137}Cs and ^{131}I that have been proved to play a part in the contamination of foodstuffs that results from nuclear weapons testing (cf. e.g., UN 77).

In the BWR-2 case these nuclides would indeed be of importance, although ^{134}Cs would also play a role. The latter has a half-life of 2.06 years and behaves as the longer-lived ^{137}Cs. Therefore, taking into account the shorter half-life, the transfer factors for ^{134}Cs can be estimated on the basis of those for ^{137}Cs. If it is assumed that there is a delay between the contamination of the field and the consumption of a foodstuff of 0.5 y on average, the transfer factor for ^{134}Cs would be approximately 0.8 times that of ^{137}Cs. If the foodstuffs produced during the first year after the accident are destroyed, the ^{134}Cs transfer factor would be 0.58 times the ^{137}Cs transfer factor then valid. If the foodstuffs produced in the second year are destroyed, too, then the transfer factor for ^{134}Cs falls to 0.44 times that for ^{137}Cs.

Table 10.4 shows the transfer factors used in the calculations of ^{90}Sr, ^{137}Cs and ^{131}I in, respectively, 1) the year of the accident (year 0), 2) one year after the accident - the foodstuffs produced during the year of the accident are assumed destroyed - and 3) two years after the accident - the foodstuffs produced in the year following the year of the accident are also presumed destroyed, etc. Because of the short half-life of ^{131}I it only plays a part in the year of the accident. As a result of the poor take-up of ^{137}Cs from the soil via roots, this nuclide, too, would primarily be important during the year of the accident. On the other hand, because ^{90}Sr is easily taken up by crops via the root net, this nuclide is of long-term significance. Even if, for instance, crops were destroyed every year for four years following the accident, the committed effective dose equivalent from ^{90}Sr in milk would only be rather more than halved, and in the case of vegetables there is only a reduction of hardly 20%.

The transfer factors shown in table 10.4 are calculated on the basis of measurements of radioactive fallout in eastern Denmark.

This means that a seasonal distribution is used that corresponds to that of the fallout. Therefore the months May to August are given the greatest weight because the majority of fallout occurs at this season owing to different meteorological factors. If, instead, all months of the year are weighted equally, the transfer factors would have been smaller as crops are most sensitive to contamination in the period May to August.

In winter, for example, there are hardly any crops on the fields and the transfer factors will therefore be smaller at this season: for ^{131}I they would actually be zero. If contamination occurred in May-August, the transfer factors would, on the other hand, be larger than those used here. Averaged over the year, however, the factors used would give an over-estimation.

Table 10.4. Transfer factors (pCi kg^{-1} y per mCi km^{-2}) from deposition to foodstuffs and fodder produced in East Denmark. Based on fallout data

Year from which contaminated products start to be used (year of accident = 0)	^{90}Sr					^{137}Cs *)					^{131}I
	0	1st	2nd	3rd	4th	0	1st	2nd	3rd	4th	0
Rye	24	2.6	2.5	2.5	2.4	42	0	0	0	0	-
Wheat	20	6.3	5.9	5.5	5.1	24	0	0	0	0	-
Oats	30	17.3	16.9	16.5	16.1	26	0	0	0	0	-
Leaf vegetables	7	6.4	6.4	6.1	5.9	1.3	0.5	0.5	0.4	0.4	0.2
Root vegetables	4.9	4.6	4.3	4	3.7	1.8	0.3	0.3	0.2	0.2	-
Potatoes	2.7	2.5	2.5	2.4	2.4	3.3	0	0	0	0	-
Apples	1.4	0.3	0.3	0.3	0.3	4	1.9	0.8	0.4	0.2	-
Soft fruit	10.6	10.2	10	9.6	9.2	2.6	0	0	0	0	-
Milk	3.35	2.4	2	1.8	1.6	4.3	1.2	0.4	0.4	0.3	0.6
Beef	1.4	0.9	0.8	0.8	0.7	27	3	3	2	1	-
Pork	0.8	0.8	0.7	0.7	0.6	34	18	2	1	0.5	-
Eggs	1.2	0.6	0.5	0.4	0.3	1.8	0.9	0.3	0.3	0.2	-
Grass	68	32	13	9	7	27	9	8	7	6.5	50
Beet	13.9	12.4	12	11	10	0.8	0	0	0	0	-
Beet tops	111	97	97	95	93	13	3.3	3.3	3.2	3.1	-
Straw	180	53	50	47	45	56					-
Barley	18	5.3	5.0	4.7	4.5	28	0	0	0	0	-

*) For ^{137}Cs, direct contamination is entirely dominant. However, this does not mean that uptake by roots can be entirely ignored but that it will be minimal (transfer factor to grain $\lesssim$ 0.1).

There is a further factor that contributes to an over-evaluation of the transfer of activity from deposition to the human diet. In the case of grain, it is reckoned that this is consumed as a whole grain and not, as is actually the case at least for wheat, in the form of flour with an extraction factor of 70-75%. This would reduce the ^{90}Sr levels in wheat by a factor of approx. 5 and ^{137}Cs by a factor of approx. 2.

For milk, no allowance is made for the fact that a substantial share of the milk produced is used for the manufacture of cheese and butter. Some of the whey and skimmed milk for this production, which would contain both ^{137}Cs and ^{90}Sr, is used as livestock fodder and is thus not directly included in the human diet, as here assumed. As a result, the ^{90}Sr that is assumed to be consumed from milk is over-estimated by a factor of approx. 1.7, ^{137}Cs by a factor of approx. 2.6, and ^{131}I by a factor of approx. 6. As the uncertainty of the transfer factors is about 30%, and because there is considerable uncertainty relating to other factors included in the calculations of the foodstuff contamination that would result in the BWR-2 case, there are hardly grounds for a further refinement of the calculations.

With regard to other radionuclides, ^{89}Sr and ^{140}Ba have such short half-lives that they would only be found in products harvested in the year of the accident. Before these reached consumers, however, the radionuclides would have decayed considerably - ^{89}Sr is reduced by a factor 12 in six months and ^{140}Ba by a factor 2×10^4. ^{106}Ru would also give the majority of its committed effective dose equivalent during the first year, and as its transfer factor from deposition to the human diet is hardly half that of radiocaesium, the committed effective dose equivalent from ^{106}Ru would in any case be an order of magnitude less than the contribution from radiocaesium. The amounts of plutonium and americium are so small that they play no part, and, moreover, their transfer factors are significantly smaller than those of ^{90}Sr and ^{137}Cs. For comparison, the ^{239}Pu release in the BWR-2 case is roughly three times as great as the existing amount of plutonium fallout on Zealand from nuclear weapons testing, and the amount of ^{241}Am in the release is of the same magnitude as the amount of radioactive fallout of americium.

10.3. Inventory and dose calculations relating to agricultural production on Zealand contaminated in the BWR-2 case

Using the tables of products 10.1-3, and multiplying by the transfer factors in table 10.4, the inventories of agricultural products from the different districts can be calculated with respect to ^{90}Sr, ^{137}Cs and ^{131}I for a so-called unit deposition (1 mCi km^{-2} of the radionuclide concerned). If these figures are multiplied by the assumed depositions in the BWR-2 case (cf. table 10.5), tables 10.6-11 can be calculated.

Only the inventories of ^{90}Sr, ^{137}Cs and ^{131}I are given here, but an estimate of the inventories of ^{134}Cs can be obtained by multiplying the inventories of ^{137}Cs in the three tables by the relation between ^{134}Cs and ^{137}Cs in the release, i.e., 0.664, and then multiplying by, respectively, 0.80, 0.58 and 0.44, i.e., the respective relative transfer factors for ^{134}Cs as given earlier.

The collective committed effective dose equivalents are calculated for ^{90}Sr, ^{137}Cs, ^{134}Cs and ^{131}I. These values are calculated on the basis of the inventories by dividing by the ALI values of the radionuclides (in mCi) and multiplying by 5, the ALI value being the amount of activity consumed in the course of a year together with foodstuffs that will result in a committed effective dose equivalent of 5 rem (0.05 Sv).

For ^{90}Sr, the doses thus calculated are divided by 3 because the ICRP calculation does not take into account the high content of calcium in the Danish diet (620 g annually per capita). Should the foodstuffs be exported to countries with little calcium in the diet ($\lesssim$ 200 g annually per capita) it would be correct to use the ALI values without this adjustment. However, it should be noted that exports mainly comprise animal products with a relatively low strontium content (pork, butter, eggs).

Table 10.5. The deposition (Ci/km^2) in the different districts (cf. fig. 10.1) in the BWR-2 case (stability F, u = 5 m/s, v_g = 2 cm/s[1]))

District	^{90}Sr	^{137}Cs	^{131}I
C8	2	15	230
C9	450	2850	46500
C10	2	13	200
D9	250	1600	25500
D10	1	4	70
E9	140	900	14900
E10	0.3	2	30
F8	0.1	0.5	10
F9	70	450	7100
F10	0.1	0.5	10
G8	0.02	0.2	2.5
G9	30	200	3000
G10	0.04	0.3	4
H8	0	0.04	0.5
H9	12	75	1500

1) This deposition velocity implies that about 95% of the fallout occurs inside a distance of 130 km fra Barsebäck. A smaller v_g value (cf. chapter 4) reduces the fallout on Zealand, but this would spread more activity further out to Funen and Jutland. However, the manrem doses arising from foodstuffs are not significantly smaller if v_g is reduced to, e.g., 1 cm/s.

Table 10.6. BWR-2 case. Inventories in foodstuffs and fodders calculated from the year of the accident onwards

District	Ci ^{90}Sr			Ci ^{137}Cs			Ci ^{131}I		
	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders
C8	0.1	0	1	0.5	0	3	0.07	0	38
C9	0	0	0	0.1	0	0	0.05	0	0
C10	0.1	0	1	0.8	0.1	3	0.01	0	61
D9	10.3	0.06	166	80	4.8	500	2.7	0.6	3600
D10	0.1	0	4	0.5	0.1	6	0.01	0.1	110
E9	47	2.0	1080	380	95	3100	7.0	30	3000
E10	0.1	0.01	3	0.6	0.3	8	0	0.2	110
F8	0.1	0.01	2	0.4	0.2	3	0	0.1	43
F9	49	6.4	1620	390	220	4300	3.3	103	4900
F10	0	0.01	2	0.3	0.1	3	0	0.1	54
G8	0	0	0	0.2	0.1	2	0	0	14
G9	43	7.4	1660	350	260	4200	2.4	116	5000
G10	0	0	1	0.2	0.1	2	0	0	24
H8	0	0	0	0.1	0	1	0	0	7
H9	26	4.3	1180	197	155	2400	1.8	84	3100

Table 10.7. BWR-2 case. Collective doses from foodstuffs produced in the districts[1] calculated from the year of the accident onwards.

District	Mmanrem				
	^{90}Sr	^{137}Cs	^{134}Cs	^{131}I	Σ
C8	0	0.02	0.01	0	0
C9	0	0	0	0	0
C10	0	0.04	0.03	0	0.1
D9	0.64	3.9	2.7	0.15	7.4
D10	0	0.03	0.02	0	0.1
E9	3.0	22	15	1.71	42
E10	0	0.04	0.03	0.01	0.1
F8	0	0.03	0.02	0	0.1
F9	3.4	28	20	4.9	56
F10	0	0.02	0.01	0.01	0
G8	0	0.01	0.01	0	0
G9	3.1	28	20	5.5	57
G10	0	0.01	0.01	0	0
H8	0	0	0	0	0
H9	1.87	16.3	11.4	4.0	34
Σ Mmanrem	12.0	98	69	16.3	196

[1] Note: The doses need not necessarily appear in the districts concerned because foodstuffs are often consumed in areas other than those in which they are produced.
As the division into sectors is arbitrary, only part of the area in sector 9 might be so heavily contaminated as to require intervention.

Table 10.8. BWR-2 case. The inventories in foodstuffs and fodders produced in the districts calculated from the year after the accident onwards - i.e., foodstuffs produced during the year of the accident are destroyed.

District	Ci ^{90}Sr			Ci ^{137}Cs		
	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders
C8	0	0	0.6	0	0	0.5
C9	0	0	0	0	0	0
C10	0	0	0.5	0	0	0.7
D9	3.6	0	59	1.2	2.3	41
D10	0	0	1.6	0	0.1	1.1
E9	16.1	1.5	440	3.3	45	340
E10	0	0	1.3	0	0.1	1.4
F8	0	0	0.8	0	0.1	0.4
F9	16.3	4.8	760	1.9	98	610
F10	0	0	0.9	0	0.1	0.5
G8	0	0	0.2	0	0	0.2
G9	15.2	5.4	830	1.8	115	660
G10	0	0	0.4	0	0	0.4
H8	0	0	0.3	0	0	0.1
H9	9.3	3.2	680	1.0	70	350

Table 10.9. BWR-2 case. The collective doses from foodstuffs produced in the districts calculated from the year after the accident onwards.

District	Mmanrem			
	^{90}Sr	^{137}Cs	^{134}Cs	Σ
C8	0	0	0	0
C9	0	0	0	0
C10	0	0	0	0
D9	0.23	0.16	0.08	0.5
D10	0	0	0	0
E9	1.10	2.2	1.12	4.4
E10	0	0.01	0	0
F8	0	0.01	0	0
F9	1.30	4.6	2.3	8.2
F10	0	0	0	0
G8	0	0	0	0
G9	1.27	5.4	2.8	9.5
G10	0	0	0	0
H8	0	0	0	0
H9	0.77	3.3	1.68	5.8
Σ Mmanrem	4.7	15.7	8.0	28

Table 10.10. BWR-2 case. The inventories in foodstuffs and fodders produced in the districts calculated from the second year after the accident onwards - i.e., foodstuffs in the year of the accident and the following year are destroyed.

District	Ci ^{90}Sr			Ci ^{137}Cs		
	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders
C8	0	0	0.4	0	0	0.5
C9	0	0	0	0	0	0
C10	0	0	0.2	0	0	0.6
D9	3.5	0	43	0.8	0.3	37
D10	0	0	1.0	0	0	1.0
E9	15.4	1.3	320	2.1	6.5	310
E10	0	0	0.9	0	0	1.2
F8	0	0	0.6	0	0	0.4
F9	15.6	4.0	560	1.2	15.5	540
F10	0	0	0.6	0	0	0.5
G8	0	0	0.2	0	0	0.2
G9	14.5	4.6	630	1.3	18.3	590
G10	0	0	0.3	0	0	0.3
H8	0	0	0.2	0	0	0.1
H9	8.9	2.7	570	0.7	10.8	320

Table 10.11. BWR-2 case. Collective doses from foodstuffs produced in the districts calculated from the second year after the accident onwards.

District	Mmanrem			
	^{90}Sr	^{137}Cs	^{134}Cs	Σ
C8	0	0	0	0
C9	0	0	0	0
C10	0	0	0	0
D9	0.22	0.05	0.02	0.3
D10	0	0	0	0
E9	1.03	0.04	0.16	1.6
E10	0	0	0	0
F8	0	0	0	0
F9	1.2	0.77	0.30	2.3
F10	0	0	0	0
G8	0	0	0	0
G9	1.17	0.91	0.35	2.4
G10	0	0	0	0
H8	0	0	0	0
H9	0.70	0.53	0.21	1.4
Σ Mmanrem	4.3	2.7	1.0	8

Table 10.7 shows that 99.9% of the total collective dose equivalent from the consumption of contaminated food produced on Zealand originates from the districts D9, E9, F9, G9 and H9, which cover a total area of 3500 km^2, i.e., about half the area of Zealand. On the other hand, the sector division does not make it possible to determine whether the contamination is concentrated in a narrow belt inside this area.

A comparison of tables 10.7 and 10.9 shows that the destruction of foodstuffs (but not of livestock fodders) during the year of the accident reduces the collective dose by 169 Megamanrem. If the value of a manrem is set at 100 Danish kroner, this reduction represents 17 $\times$ 10^9 kroner. As the value of Denmark's harvest (in 1976) was some 30 $\times$ 10^9 kroner, and because the area concerned comprises less than 10% of the agricultural land of the country, it is obvious that the foodstuffs should be destroyed. In the following year the value of the foodstuffs will be a little more than the value of the collective dose; here, too, foodstuffs would probably be destroyed. However, it would of course be preferable to alter agricultural production so that it would be unnecessary to destroy any foodstuffs other than from the year in which the accident occurred.

It should be possible to limit the destruction of foodstuffs during the year of the accident to the crops standing on the fields at the time it took place. Moreover, livestock could be saved if housed and fed on uncontaminated fodder, or perhaps evacuated to other parts of the country. Section 10.5 gives more details of which long-term measures could reduce the doses originating from agricultural products produced in the contaminated area.

10.4. Inventory and dose calculations for agricultural production on Zealand contaminated in the BWR-3 case

Analogous with the calculations in 10.3, inventories and doses can be calculated for the BWR-3 case. Table 10.12 shows the depositions in the different sectors and tables 10.13-18 are analogous to tables 10.6-11.

It appears that the BWR-3 case would result in foodstuff doses approximately one order of magnitude less than the doses resulting from the BWR-2 case. It would, however, still be necessary to take certain measures during the year following the accident; if no action was taken doses would be approximately 2×10^7 manrem ~ 2×10^9 kr. (1 manrem ~ 100 kr.), or of nearly the same magnitude as the value of the annual agricultural production of the area concerned ~ 2.5×10^9 kr.

Table 10.12. BWR-3 case. Deposition (Ci/km^2) in the districts (cf. fig. 10.1). Stability D, u = 10 m/s, v_g = 2 cm/s

District	^{90}Sr	^{131}I	^{137}Cs
C8	0.03	3	0.3
C9	14	2000	175
C10	0.03	3	0.3
D9	8	900	100
D10	0.01	1	0.1
E9	5	575	65
E10	0	0.3	0
F8	0	0.1	0
F9	3	350	40
F10	0	0.1	0
G8	0	0.1	0
G9	2	210	25
G10	0	0.1	0
H8	0	0	0
H9	1.5	165	20

Table 10.13. BWR-3 case. Inventories in foodstuffs and fodders calculated from the year of the accident onwards.

District	Ci ^{90}Sr			Ci ^{137}Cs			Ci ^{131}I		
	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders
C8	0	0	0	0	0	0.1	0	0	0.5
C9	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0.1	0	0	0.9
D9	0.3	0	5.3	5.0	0.3	31	0.1	0	127
D10	0	0	0	0	0	0.1	0	0	1.6
E9	1.7	0.1	39	27	6.9	220	0.3	1.1	1160
E10	0	0	0	0	0	0.1	0	0	1.1
F8	0	0	0	0	0	0.1	0	0	0.4
F9	2.1	0.3	69	35	19.6	380	0.2	5.1	2400
F10	0	0	0	0	0	0.1	0	0	0.5
G8	0	0	0	0	0	0	0	0	0.3
G9	2.9	0.5	111	44	32	520	0.2	8.1	3500
G10	0	0	0	0	0	0	0	0	0.3
H8	0	0	0	0	0	0	0	0	0.3
H9	3.2	0.5	148	53	41	640	0.2	9.2	3400

Table 10.14. BWR-3 case. Collective doses from foodstuffs produced in the districts[1)] calculated from the year of the accident onwards.

District	Mmanrem				
	^{90}Sr	^{137}Cs	^{134}Cs	^{131}I	Σ
C8	0	0	0	0	0
C9	0	0	0	0	0
C10	0	0	0	0	0
D9	0.02	0.24	0.17	0.01	0.43
D10	0	0	0	0	0
E9	0.11	1.59	1.08	0.07	2.8
E10	0	0	0	0	0
F8	0	0	0	0	0
F9	0.15	2.5	1.78	0.24	4.7
F10	0	0	0	0	0
G8	0	0	0	0	0
G9	0.21	3.5	2.5	0.38	6.6
G10	0	0	0	0	0
H8	0	0	0	0	0
H9	0.23	4.3	3.0	0.44	8.0
Σ Mmanrem	0.71	12.1	8.5	1.13	22.5

1)Cf. notes to table 10.7.

<u>Table 10.15</u>. BWR-3 case. The inventories in foodstuffs and fodder produced in the districts calculated from the year after the accident onwards - i.e., foodstuffs produced in the year of the accident are destroyed.

District	Ci ^{90}Sr			Ci ^{137}Cs		
	Veg. foodstuffs	Animal foodstuffs	Veg. fodders	Veg. foodstuffs	Animal foodstuffs	Veg. fodders
C8	0	0	0	0	0	0
C9	0	0	0	0	0	0
C10	0	0	0	0	0	0
D9	0.1	0	1.9	0.1	0.1	2.6
D10	0	0	0	0	0	0
E9	0.6	0.1	15.7	0.2	3.2	25
E10	0	0	0	0	0	0
F8	0	0	0	0	0	0
F9	0.7	0.2	33	0.2	8.7	54
F10	0	0	0	0	0	0
G8	0	0	0	0	0	0
G9	1.0	0.4	55	0.2	14.4	82
G10	0	0	0	0	0	0
H8	0	0	0	0	0	0
H9	1.1	0.4	85	0.3	18.7	93

Table 10.16. BWR-3 case. Collective doses from foodstuffs produced in the districts calculated from the year after the accident onwards.

District	Mmanrem			
	^{90}Sr	^{137}Cs	^{134}Cs	Σ
C8	0	0	0	0
C9	0	0	0	0
C10	0	0	0	0
D9	0.01	0.01	0	0.02
D10	0	0	0	0
E9	0.04	0.16	0.08	0.28
E10	0	0	0	0
F8	0	0	0	0
F9	0.06	0.41	0.20	0.67
F10	0	0	0	0
G8	0	0	0	0
G9	0.09	0.68	0.35	1.12
G10	0	0	0	0
H8	0	0	0	0
H9	0.10	0.88	0.45	1.43
Σ Mmanrem	0.28	2.1	1.09	3.5

Table 10.17. BWR-3 case. The inventories in foodstuffs and fodder produced in the districts calculated from the second year after the accident onwards - i.e., foodstuffs from the year of the accident and the following year are destroyed.

District	Ci ^{90}Sr			Ci ^{137}Cs		
	Veg. food-stuffs	Animal food-stuffs	Veg. fodders	Veg. food-stuffs	Animal food-stuffs	Veg. fodders
C8	0	0	0	0	0	0
C9	0	0	0	0	0	0
C10	0	0	0	0	0	0
D9	0.1	0	1.4	0	0	2.3
D10	0	0	0	0	0	0
E9	0.6	0	11.4	0.2	0.5	22
E10	0	0	0	0	0	0
F8	0	0	0	0	0	0
F9	0.7	0.2	24	0.1	1.4	48
F10	0	0	0	0	0	0
G8	0	0	0	0	0	0
G9	1.0	0.3	42	0.2	2.3	74
G10	0	0	0	0	0	0
H8	0	0	0	0	0	0
H9	1.1	0.3	71	0.2	2.9	85

Table 10.18. BWR-3 case. Collective doses from foodstuffs produced in the districts calculated from the second year after the accident onwards.

District	Mmanrem			
	^{90}Sr	^{137}Cs	^{134}Cs	Σ
C8	0	0	0	0
C9	0	0	0	0
C10	0	0	0	0
D9	0	0	0	0.01
D10	0	0	0	0
E9	0.04	0.03	0	0.08
E10	0	0	0	0
F8	0	0	0	0
F9	0.05	0.07	0.03	0.15
F10	0	0	0	0
G8	0	0	0	0
G9	0.08	0.11	0.04	0.24
G10	0	0	0	0
H8	0	0	0	0
H9	0.09	0.14	0.06	0.28
Σ Mmanrem	0.26	0.36	0.14	0.75

10.5. Alterations in agricultural production that might be necessary to reduce doses

Because, as appears from the foregoing, ^{90}Sr disappears only slowly from foodstuffs, while ^{137}Cs, ^{134}Cs and ^{131}I vanish relatively rapidly, it is desirable to produce such foodstuffs that have low transfer factors for ^{90}Sr: these are beef, pork and eggs. If, furthermore, the ^{90}Sr levels are to be kept as low as possible in these products, i.e., the transfer factors should be reduced, then grain (rye and barley), potatoes, and grass should be cultivated chiefly, any milk being used for butter and the skimmed milk fed to pigs.

Taking the most extreme action then, the contaminated areas should be used only for crops that do not transfer ^{90}Sr to foodstuffs. They could perhaps be used for seed-growing and the cultivation of seed grain. Cultivation of sugar beet and potatoes leading to a production of refined agricultural products could also be envisaged. These would contain virtually no activity.

In the following an example is given of a calculation of the effects on doses of a re-organisation of agricultural production.

The most heavily contaminated area (sector 9 on fig. 10.1) comprises approximately 2500 km^2 of agricultural land. If this is used exclusively to cultivate grain, and reckoning with a yield of 470 t per km^2 (the average for grain-growing areas on Zealand), then 1 175 000 tons of grain would be produced annually. Using this exclusively to feed pigs - 5 kg of grain are needed to produce 1 kg pork - production would be 235 000 tons of pork per year. Sector 9 produces about 107 000 tons of meat (and eggs) annually, i.e., meat production in this area could be doubled if grain alone is cultivated and then fed to pigs.

Envisaging that this alteration in production takes place already in the year following that of the accident, and furthermore that foodstuffs and fodder from the year of the accident have been destroyed, the inventory in fodder (barley grain) produced in the second year will be 234 Ci ^{90}Sr, as the amount of radiocaesium is minimal (see the footnote to table 10.4), and the straw from the grain is destroyed. This is a reduction in the ^{90}Sr content of the fodder by a factor 9. If this grain is used for pig production, the inventory in the pork will be:

$$\frac{0.109 \times 235000 \times 234}{1175000} = 5.1 \text{ Ci } ^{90}\text{Sr}$$

as 0.109 is the relation between the ^{90}Sr concentrations in pork and barley calculated on the basis of the concentrations in sector 9 in the year of the accident.

The collective committed effective dose equivalent from this amount of ^{90}Sr will be $(5.1 \times 0.5):(8.1 \times 10^{-6}) = 0.31$ Mmanrem; 235 000 tons of pork correspond to the annual consumption of pork of $(235 \times 10^6):40 = 5.88 \times 10^6$ people, i.e., the average committed effective individual dose equivalent will be 53 mrem. Comparing the collective dose with that in table 10.12, it appears that a re-organisation of agricultural production gives a dose reduction of a factor of approx. 25.

Imagining that barley, moreover, contains ^{137}Cs corresponding to the transfer factor 0.1 pCi ^{137}Cs kg^{-1} y $(mCi\ km^{-2})^{-1}$, the collective dose from this would be about 0.28 Mmanrem, i.e., of the same magnitude as the ^{90}Sr dose (barley conc. = pork conc. = 26 nCi kg^{-1}; consumption ~ 6 Ci ^{137}Cs with pork).

10.6. Doses originating from marine products

Considering the BWR-2 case, 1.07×10^5 Ci ^{90}Sr, 1.11×10^7 Ci ^{131}I, 6.84×10^5 Ci ^{137}Cs and 4.54×10^5 Ci ^{134}Cs would fall into the Sound. Through Danish waters there flows a north-running surface current from the Baltic of approx. 10^3 km^3 per year and a south-running current from the North Sea of approx. 5×10^2 km^3 per year. The mean retention time for activity in the Sound, which contains only some few km^3, will therefore be very short, and in the present calculations it is assumed that inner Danish waters can be considered as part of the Baltic and that one-third of the activity from the accident is distributed in the Baltic area, two-thirds in the North Sea.

10.6.1. The Baltic area (BWR-2 case)

The Baltic contains 2×10^4 km^3 water and the mean retention time for a substance that only disappears as a result of the replacement of the water masses is 20-30 y (~ 25 y) (CEC 79). The annual catch of fish in the Baltic is 8×10^8 kg. Fallout measurements have shown that about one-third of the amount of ^{137}Cs in the Baltic is found in the sediments and that the concentration factor for sea water to fish is approx. 10^2 for caesium.

The concentration factor for ^{90}Sr is approx. 1, for which reason this substance can be disregarded in this connection. The half-life of ^{131}I is so short that this, too, is of no significance. The mean retention time in the Baltic area (T_{ef}) is found to be,

for ^{137}Cs, 15.85 y $\left(\frac{1}{T_{ef}} = \frac{1}{30/\ln 2} + \frac{1}{25}\right)$

and similarly, for ^{134}Cs, 2.66 y.

^{137}<u>Cs</u>

Sea water conc.: $\dfrac{6.84 \times 10^5 \times 10^{12} \times 0.7}{3 \times 2 \times 10^{16}}$ pCi l^{-1} = 8 pCi l^{-1}

The time-integrated concentration: $8 \times 15.85 = 126$ pCi l^{-1} y.

In fish: $126 \times 10^2 = 12600$ pCi kg^{-1} y.

In consumer fish: $126000 \times 8 \times 10^8 : 10^9 = 10000$ mCi

Collective dose: $\dfrac{10000 \times 5}{0.108 \times 10^6} = 0.5$ Mmanrem

^{134}Cs

Sea water conc.: = 5.3 pCi l^{-1}

The time-integrated concentration: = 14 pCi l^{-1} y

In fish: = 1400 pCi kg^{-1} y

In consumer fish: 1100 mCi

Collective dose: = 0.07 Mmanrem

10.6.2. The North Sea (BWR-2 case)

The North Sea contains 7×10^4 km^3, and the mean retention time for a substance that only disappears as a result of the replacement of the water masses is approximately 3.5 year (CEC 79).

The annual catch of consumer fish in the North Sea is approx. 2×10^9 kg. The sedimentation of caesium in the North Sea is estimated to be about 10%. The concentration factor from sea water to fish is 50 for radiocaesium. As in the case of the Baltic, ^{90}Sr and ^{131}I are disregarded.

The mean retention time in the North Sea is:

for ^{137}Cs, 3.24 y

and, for ^{134}Cs, 1.6 y.

^{137}Cs:

Sea water concentration: = 5.9 pCi l^{-1}

The time-integrated concentration: = 19 pCi l^{-1} y

In fish: 950 pCi kg^{-1} y

In consumer fish: 1900 mCi

Collective dose: 0.09 Mmanrem

^{134}Cs

Sea water concentration: 3.9 pCi l^{-1}

The time-integrated concentration: 6 pCi l^{-1} y

In fish: 300 pCi kg^{-1} y

In consumer fish: 600 mCi

Collective dose: 0.04 Mmanrem

10.6.3. Total doses from marine products in the BWR-2 case

The collective committed effective dose equivalent from the consumption of marine products in the BWR-2 case would be approximately 0.7 Mmanrem. This value would not justify the destruction of the catch from the Baltic and the North Sea.

The North Atlantic would be the final recipient of radiocaesium contamination, but the concentration here would be so low - as a result of the great dilution - that the collective dose from fish catches, which are of an order of magnitude of 10^9 kg per annum in this area, would be negligible compared with doses from the Baltic and the North Sea area.

Run-off from the contaminated land could slightly increase the concentration in the sea, but this would be only of an order of magnitude of 10%.

An attempt can be made to estimate the collective dose from the contamination of marine foodstuffs in a different way.

In the North Sea and Baltic area, the average fish catch is 1600 kg km^{-2} y^{-1}. The transfer factor for ^{137}Cs to cod from fall-out is in Danish waters calculated to be 20 pCi kg^{-1} y (mCi $km^{-2})^{-1}$ (Aa 79). Assuming that the 7×10^5 Ci ^{137}Cs from the accident is distributed over one km^2, then the time-integrated amount of ^{137}Cs in the catch would be:

$$\frac{7 \times 10^5 \times 10^3 \times 20 \times 1600}{10^9} \text{ mCi} = 22 \text{ Ci } ^{137}\text{Cs}$$

and the collective dose from this would be approx. 1 Mmanrem.

Assuming that the relation between ^{134}Cs and total caesium dose is 14%, the dose from radiocaesium will be a total of 1.15 Mman-rem, if all fish consumed are cod. Because a considerable part of the catch consists of fish that contain less activity than cod, there is good agreement between this estimate and that made above.

10.6.4. Total doses from marine products in the BWR-3 case

In the BWR-3 case the doses would be reduced to approx. 0.2×10^6 manrem compared with the 1×10^6 manrem in the BWR-2 case, because the deposition of radiocaesium in the Sound from the former situation is about 16% of that of the latter.

10.7. Supplies of drinking water

Drinking water in Denmark originates primarily from ground water, a small share from surface water. Risø's investigations (Aa 79) of the ^{90}Sr concentrations in ground water, drinking water and lake/river water collected from all parts of the country during the last twenty years gave the results summar-ized in the following table.

Table 10.19. Transfer factors [pCi l^{-1} y per mCi km^{-2}] for ^{90}Sr from fallout to fresh water

Ground water	0.007
Drinking water	0.005
River water	0.3
Lake water	0.9

Water supplies for Copenhagen are derived from a little lake water in addition to ground water. Table 10.19 shows, however, that the ^{90}Sr concentration in drinking water could be reduced if surface water was excluded from the water supply. But measurements carried out on drinking water in Copenhagen make it clear that contributions of surface water to this are so small that the drinking water can be considered as virtually pure ground water.

Comparing the contributions to the dose from ^{90}Sr in the diet with the contributions from drinking water, we find that 1 mCi ^{90}Sr km^{-2} results in a total consumption with food of 3000 pCi ^{90}Sr per person, while the intake with drinking water is 3 pCi ^{90}Sr, i.e., 1 o/oo. Had the drinking water been derived from the average Danish lake water, the intake would have been 540 pCi or 18% of the intake with food.

The amount of ^{137}Cs released in the BWR-2 case would be some ten times greater than the amount of ^{90}Sr, but ^{137}Cs is more effectively retained in Danish soil than is ^{90}Sr, and the transfer factors for ^{137}Cs from fallout to fresh water would therefore be smaller than for ^{90}Sr. Measurements of ^{137}Cs in Danish rivers and lakes make it possible to assume that the transfer factors for ^{137}Cs from fallout to fresh water are approximately 10% of the values given in table 10.19. This means that the contribution of ^{137}Cs from drinking water could be negligible (< 0.1 o/oo) compared with the contribution from the diet (5600 pCi ^{137}Cs per person per mCi ^{137}Cs km^{-2}), which again would only contribute at most one third of the dose received from external radiation originating from the ^{137}Cs deposited on the ground.

Radionuclides other than ^{90}Sr and ^{137}Cs would not occur in any significant amounts in Danish drinking water after a core-melt accident at Barsebäck.

To conclude, the contributions from the contamination of drinking water by radionuclides released in a core-melt accident at Barsebäck would be insignificant.

10.8. Summary

Based on the possible alterations in agricultural production outlined in 10.5, a minimum of five options exist. Here it is assumed that the accident occurs in May of year 0, i.e., at a season when cattle have begun to graze the fodder (grass) of year 0, and when the crops (grain, vegetables, roots, etc.) are above ground and thus sensitive to direct contamination. The options are:

1) No action is taken after the accident.

2) Foodstuffs produced in sector 9 during the twelve months following the accident, i.e., produced in the period May (0) to April (1) are destroyed.
   This means that vegetable foodstuffs (grain products, vegetables, etc.) are destroyed, that milk and eggs are discarded, and that no livestock are slaughtered; but livestock are otherwise retained and fed on the contaminated fodder produced in the area.

3) Foodstuffs produced in sector 9 during the 24 months following the accident, i.e., foodstuffs produced in the period May (0) to April (2), are destroyed.
   The procedure is that outlined under 2, i.e., crops are sown and the products used to feed livestock, but no livestock products are used for human consumption.

Table 10.20. Collective committed effective dose equivalents from foodstuffs contaminated in the BWR-2 case and the BWR-3 case

Mmanrem

	Agricultural products on Zealand		Marine products		Total	
	BWR-2	BWR-3	BWR-2	BWR-3	BWR-2	BWR-3
No foodstuffs destroyed	196	22.5	1	0.2	197	22.7
Foodstuffs produced on the soil during year "0" are destroyed	28	3.5	1	0.2	29	3.7
Foodstuffs produced on the soil during year "0" and "1" are destroyed	8	0.8	1	0.2	9	1.0
Agricultural production limited to barley and pigs	0.7	0.02	1	0.2	1.7	0.2
Agricultural production limited to seed-growing, sugar beet and potatoes	0.4	0	1	0.2	1.4	0.2

4) Crops standing on the fields in sector 9 are destroyed in year 0. Livestock are immediately housed and fed uncontaminated fodder from other parts of the country, perhaps even from abroad. From year (1) onwards sector 9 is used to produce barley, and livestock production is confined to pigs, fed on the barley produced in the area. Barley straw is destroyed.

5) Crops standing on the fields in sector 9 are destroyed in year (0). Livestock are immediately housed and fed uncontaminated fodder. From year (1) onwards sector 9 is used for the production of seed grain and for seed-growing, as also for the production of sugar beet and potatoes. The beet is used for sugar production only, beet wastes are discarded. The potatoes are used for the distillation of alcohol, wastes are discarded. Straw and hay from seed-growing are destroyed. No further livestock production takes place in this area.

Table 10.20 summarizes the consequences with regard to doses for these five options.

Although the object of the present report is to calculate the consequences of land contamination on Zealand, some supplementary calculations were made for agricultural production on the island of Funen. These were carried out exactly as for Zealand and they covered the whole of Funen as one area. The results are given in table 10.21.

Table 10.21. Collective committed effective dose equivalents resulting from the consumption of foodstuffs produced on Funen (Mmanrem) calculated from the year of the accident onwards.

Case	^{90}Sr	^{137}Cs	^{134}Cs	^{131}I	Total
BWR-2	0.4	3.6	2.5	1.3	8
BWR-3	0.1	2.7	1.9	0.6	5

Assuming that the relationship between the doses in years 0, 1 and 2 after the accident is the same on Funen as on Zealand, the dose reductions obtained by destroying the harvest from the first year on Funen are calculated as 7 Mmanrem in the BWR-2 and 4 Mmanrem in the BWR-3 case.

As the value of one year's agricultural production on Funen is 2.5×10^9 kroner (the agricultural area covers 2533 km^2 and the value of production on 1 km^2 is 10^6 kroner), and the equivalent value of 7×10^6 and 4×10^6 manrem are, respectively, 0.7×10^9 kroner and 0.4×10^9 kroner, intervention might be justified on Funen during the first year after the accident, for both types of accident, under the given assumptions.

The whole of the production on Funen need not necessarily be destroyed because contamination would not be uniformly distributed. Measurements would have to be carried out to determine the extent of intervention.

Further intervention relating to crops on Funen in the following years would hardly be justified in either case as the dose reduction would be only of the order of one Mmanrem.

As appears from the above, both cases could imply restrictions on agricultural production in parts of Zealand and perhaps also on Funen. Alterations in agricultural production in the contaminated areas would give a very significant reduction in the collective dose from foodstuffs produced on the soil. In this case marine products would be the primary source of the dose, but it would hardly be possible to reduce this significantly because it would be distributed over a large area and over a large population (the population of North Europe ~ 10^8). On the other hand, individual doses would be small (~ 10 mrem).

Incidentally, the amount of radiocaesium released to the marine environment in the BWR-2 case would be of the same order of magnitude as the release, to date, of radiocaesium from the Sellafield (Windscale) reprocessing plant in the UK.

10.9. References

Aa 79 Aarkrog, A., 1979, "Environmental studies on radioecological sensitivity and variability", Risø-R-437.

CEC 79 CEC, 1979, "Methodology for evaluating the radiological consequences of radioactive effluents released in normal operations".

Da 77 Danmarks Statistik, 1977, "Statistisk Årbog 1977". (Statistical yearbook 1977).

Da 78 Danmarks Statistik, 1978, "Landbrugsstatistik 1977". (Agricultural statistics 1977).

HASL 65 HASL, 1965, "Environmental Quarterly", October 1, 1965, HASL-164.

He 77 Hedemann Jensen, P. et al., 1977, "Calculation of the individual and population doses on Danish territory resulting from hypothetical core-melt accidents at the Barsebäck reactor", Risø-R-356.

ICRP 79 ICRP, 1979, "Limits for intake of radionuclides by workers", ICRP Publication 30, part 1.

UN 77 UNSCEAR, 1977, "Sources and effects of ionizing radiation".

11. WASTE TREATMENT

11.1. Liquid wastes

Should there occur an accident at the Barsebäck nuclear power plant in which activity is dry-deposited in the Greater Copenhagen area, the first shower of rain would wash some of the activity into the sewers, just as decontamination procedures such as the hosing of roads and buildings would carry the material washed off into the sewer system.

Sewage from the Greater Copenhagen area ends up in the filter plant Lynetten, from where water is led out into the Sound. The area is divided into four districts. Sewage from one district is given a fairly thorough purification at the Damhuså plant. Sewage from two other districts is given a rough pre-treatment and that from the last district is taken to Lynetten without any kind of pre-treatment.

At Damhuså, sludge is collected in drying beds; both the Lynetten and the Damhuså plants are modern and automatic.

Some estimates follow of the radiation levels pertaining to the sludge-drying beds and of the sewerage itself. It is assumed roughly that the Lynetten plant receives water from the area 20-26 km from Barsebäck and the Damhuså plant from the area 26-30 km from Barsebäck.

Tables 11.1 and 11.2 show the initial deposition in three 10° sectors having the main directions 239°, 249° and 259° in the BWR-2 case. Outside these three sectors, activity levels are more than two orders of magnitude lower. Assuming that a max. of 40% of the activity runs into the sewerage, e.g., after a decontamination process, the following amounts of activity

Table 11.1. Deposition of ^{137}Cs in the Greater Copenhagen area in the BWR-2 case

Distance (km) from Barsebäck	^{137}Cs deposition in the 10° segments					
	239°		249°		259°	
	kCi	$mCi \cdot m^{-2}$	kCi	$mCi \cdot m^{-2}$	kCi	$mCi \cdot m^{-2}$
20 - 22	2.26	0.31	6.8	0.93	2.13	0.29
22 - 24	3.60	0.45	10.8	1.34	3.53	0.44
24 - 26	4.90	0.56	16.5	1.89	4.84	0.56
26 - 28	7.30	0.78	24.0	2.55	7.15	0.76
28 - 30	9.65	0.95	35.2	3.47	9.95	0.98

Table 11.2. Total deposition of all depositable isotopes in the area of Greater Copenhagen in the BWR-2 case

Distance (km) from Barsebäck	Total deposition of activity in the 10° segments					
	239°		249°		259°	
	kCi	$mCi \cdot m^{-2}$	kCi	$mCi \cdot m^{-2}$	kCi	$mCi \cdot m^{-2}$
20 - 22	101	13.8	305	41.6	96	13.1
22 - 24	162	20.2	484	60.3	158	19.7
24 - 26	220	25.2	741	84.9	218	25.0
26 - 28	328	34.8	1080	115	321	34.1
28 - 30	434	42.9	1580	156	448	44.3

will end up in the Damhuså and Lynetten filter beds, respectively:

Damhuså: $1.7 \cdot 10^6$ Ci in all, of which:
$3.7 \cdot 10^4$ Ci ^{137}Cs
$2.5 \cdot 10^4$ Ci ^{134}Cs

Lynetten: $1.0 \cdot 10^6$ Ci in all, of which:
$2.2 \cdot 10^4$ Ci ^{137}Cs
$1.5 \cdot 10^4$ Ci ^{134}Cs

Assuming that the sewer system is 100 km long, a uniform distribution over the entire system of an estimated tenth of the 40% washed off, i.e. approx. 0.27 MCi, gives rise to an initial radiation level in the sewers of approx. 1 Rh^{-1}. Calculations are made for a line source of infinite length (in practice 400-500 m long) with a source strength of 0.27 MCi/100 km ~ 2.7 $Ci \cdot m^{-1}$.

The Lynetten plant produces approximately 1000 tons of dry sludge daily. This is incinerated and thus converted into 100 tons ash, which for the time being is placed in a heap facing the seashore, surrounded by a ring wall. Later it may be used for road surfacing.

Assuming that the amounts of activity given above for the Lynetten plant (no activity remaining in the sewers) are found in a heap of 1000 tons of dry sludge (incineration would be inappropriate), the radiation level would be (calculated for an upright cylinder with a radius and height of 6 m ~ 700 m^3):

Lynetten: 270 $R \cdot h^{-1}$.

After a few months, when only the caesium isotopes remain, the radiation level 1 m from the heap will be:

Lynetten: 10 $R \cdot h^{-1}$.

To avoid the accumulation of activity in sludge heaps, it would be an advantage from the viewpoint of health physics to lead the sewage from the Greater Copenhagen area round the purification plants and directly into the Sound. The total amount of activity washed off the area lying 20 to 30 km from Barsebäck comprises, namely, less than 10% of the amount of activity already deposited in the Sound as a result of the passage of the cloud.

11.2. Solid waste

Some estimations follow of the radiation levels that would result from the asphalt removed from road surfaces as a dose-reducing measure.

The asphalt is assumed to be 2 cm thick, and an estimation is made of what 10 tons of asphalt would, at worst, imply of radiation levels. The density of asphalt is 2.28 $g \cdot cm^{-3}$, and 10 tons of asphalt correspond therefore to $10/2.28 = 4.38$ m^3 asphalt. With a thickness of 0.02 m, 10 tons of asphalt would correspond to an area of $4.38/0.02 = 220$ m^2 road.

According to table 11.2, the initial surface concentration in the most highly contaminated area is approx. 0.16 $Ci \cdot m^{-2}$. 10 tons of asphalt would therefore contain a maximum of $0.16 \cdot 220 = 35$ Ci. If 10 tons of asphalt are loaded onto a lorry, and if the heap of asphalt is reckoned to be cylindrical in shape (radius of 0.6 m and length of 4 m), the radiation level at the driver's seat (0.5 m from the end surface of the cylinder) would be a maximum of approximately 200 mRh^{-1}. 5 cm of lead shielding between the driver and the waste can reduce this level to approx. 10 mRh^{-1}.

The radiation level at a distance of 4 m from the side of the lorry (corresponding to the distance to the closest pedestrian on the pavement) would be a maximum of 130 mRh^{-1} when the lorry is at a standstill. The transit dose to anyone on the pavement would be, assuming a speed of 40 $km \cdot h^{-1}$, a maximum of about

30 μR ~ 30 μrem. If the asphalt is not removed from the roads until some months after the accident, the radiation levels would be reduced to about 1/30.

11.3. Conclusions

It would be appropriate to conduct the sewage temporarily around the purification plants and directly out into the Sound. A further possibility would be to cast a concrete storage facility to hold the active sludge (700-1000 m^3) which could be placed in it by means of an excavator. After sealing the container with a layer of concrete and soil, it would give sufficient shielding to obviate the necessity of placing any restrictions on the area.

Work in the sewer system, with 4% of the deposited activity retained, could not be carried out as normal. However, it would be possible to suspend such work for some months. Even assuming that all the activity concerned (4%) did remain in the sewer system, the radiation level after some months would be reduced to approximately 30 mRh^{-1}, originating mainly from ^{137}Cs and ^{134}Cs.

The amounts of broken up asphalt could be large - approx. 2-3 m^3 per 100 m^2 of asphalted road - depending on how closely it is stacked. The amount of activity here would be a maximum 16 Ci if the asphalt is broken up immediately after the deposition of activity, and approx. 0.5 Ci if this takes place after an interval of some months.

In the case of contaminated agricultural products - e.g., field crops - destruction might be necessary, cf. chapter 10. If field crops were burnt the activity would be spread by the wind and lead to contamination elsewhere. One possibility would be to harvest the crops in the normal manner and then dispose of them. Another possibility would be to plough them into the soil. The best time for this would depend on what stage of growth the crops had reached at the time of the accident.

Disused gravel pits could be used as repositories for wastes, these being classified as low and medium active.

Sales distributors:
Jul. Gjellerup, Sølvgade 87,
DK-1307 Copenhagen K, Denmark

Available on exchange from:
Risø Library, Risø National Laboratory,
P. O. Box 49, DK-4000 Roskilde, Denmark

ISBN 87-550-0831-3
ISSN 0106-2840